

WORKING MEMORY ACTIVITY IN SINGLE WORD DECODING

Measuring the Reading-Attention Relationship: Functional Differences in Working Memory  
Activity During Single Word Decoding in Children With and Without Reading Disorder

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### **Abstract**

Working memory (WM) is linked to the development of reading skills and has been evidenced to contribute to reading comprehension difficulties in children with reading disorder (RD). Several converging models suggest WM to contribute to the development of foundational reading skills, but few studies have assessed this contribution in either typically developing readers (TD) or children with RD. In effort to bridge this gap, the current study identified whether a functional neuroimaging task could be used to identify changes in WM activity during single word reading in children with and without RD. Two groups of children (77 RD, 22 TD) aged 7-9 completed a functional magnetic resonance imaging (fMRI) task which paired reading and n-back trials to identify activation of *a priori* chosen regions of interest in the WM network during single word decoding. Trials consisted of words, pseudowords, and false font stimuli to assess WM activity between groups in relation to familiar words, unfamiliar words, and non-words. Exploratory analysis of behavioural WM correlates were assessed using measures of performance on the fMRI task as well as measures of verbal learning from the California Verbal Learning Test – Children’s version. Results show the fMRI task was able to identify WM network activity in both groups. In the RD group WM activity was indiscriminate to stimulus type and did not show any patterns of lateralization. In the TD group, WM activity was strongly left lateralized, and only detected during pseudoword reading, suggesting increases in WM activity during phonetic decoding only. Findings suggest the WM network may contribute differently to single word reading in children with and without RD and highlights the potential functional imaging may have in defining this relationship over the course of reading development.

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## Introduction

Reading is a complex skill which relies on the coordinated response and development of several separate cognitive processes. Multiple theories have addressed the role that executive functioning is thought to play in reading development through different perspectives (Gough & Tunmer, 1986; Pugh et al., 2001; Reynolds, 2000). A commonality across these models suggests executive functioning underlies the development and refinement of early reading skills. Failure to properly refine these early skills may lead to slower and more error prone reading as an outcome and may suggest a source for the development of reading disorders (Fischbach et al., 2014; Fletcher et al., 2011; Hulme & Snowling, 2016; Kendeou et al., 2009; Schlaggar & Church, 2009).

Despite converging theoretical basis, cognitive research on reading has not been able to consistently characterize the relationship between executive functioning and reading development (Church et al., 2019). Recent research suggests neuroimaging may be a more sensitive tool to detect the interaction between executive functioning and early reading skills based on anatomical activation (Aboud et al., 2018; Nugiel et al., 2019). Reliable identification of this relationship may be critical to our understanding of reading acquisition and improve the efficacy of reading programs and interventions.

The present study uses functional neuroimaging to isolate working memory activity during a reading task in a group of elementary school aged children with and without reading disorder. The following review will address current reading literature through three perspectives; developmental, cognitive, and biological. In addition, reading disorders, executive functioning,

and the neuroanatomy of reading systems will each be discussed within the context of relevant models of reading development.

### **Reading Disorder**

Reading disorder (RD) is a specific learning disorder with a strong genetic basis that is characterized by persistent challenges in the fluency and accuracy of skills such as word reading, decoding, spelling, and reading comprehension (Lyon et al., 2003). These challenges are not due to deficits of sensory systems or intelligence, and are better attributed to disruptions in the connection and development of multiple brain regions – each of which may successfully perform many other tasks on their own, but struggle to coordinate with the same efficiency during the act of reading (D’Mello & Gabrieli, 2018; Shaywitz et al., 2002). Individuals with RD tend to read at a significantly lower level than their peers regardless of age (Lyon et al., 2003). The prevalence of RD varies widely based on diagnostic criteria, language structure, and environmental factors but is commonly thought to occur at rates of 3-7% in English speaking populations (Wagner et al., 2020).

RD is primarily identified in childhood when poor development of reading skills become apparent through school, but there is strong evidence to suggest that neurobiological differences in children with familial risk for RD may be apparent at pre-school ages (Vandermosten et al., 2016). Genetic-imaging studies have demonstrated the effect of a number of dyslexia risk genes on neurodevelopment, and cite the heritability of RD to be 54-84% (Eicher & Gruen, 2013). RD is persistent and carries into adulthood in the majority of cases, it is often found to be comorbid with other developmental and language disorders such as attention-deficit/hyperactivity disorder (ADHD) and specific language impairment (SLI), which can further complicate development

and result in poor literacy skills (Smirni et al., 2020; Snowling & Hulme, 2012; Tannock et al., 2018). The cumulative effects of RD understandably result in personal impacts on academic achievement, job performance, and mental health (D’Mello & Gabrieli, 2018; Tannock et al., 2018), while the large genetic and environmental influence of the disorder suggests an intergenerational effect that may cause further academic, occupational, and socioeconomic disadvantages within the population (Greenberg et al., 2013).

The specific verbal skills which are primarily affected by RD are somewhat variable. While the majority of people with RD experience difficulties in decoding print (which can result in poor reading fluency and comprehension – the classic definition of developmental dyslexia), others have specific difficulties with reading comprehension, due to underlying issues with understanding word meanings or grammatical structure (Hulme & Snowling, 2016). There is ongoing discussion into the behavioural, genetic, and neurobiological differences between the different ‘types’ of reading disorder and how they should be classified (Snowling & Hulme, 2012). Nevertheless, all manifestations of RD affect reading comprehension, as a result of deficiencies in underlying skills, all negatively impact literacy skills and academic outcomes, and all can be greatly mitigated through implementation of targeted early intervention (Shaywitz et al., 1992). This study will primarily discuss the relationship between decoding and reading comprehension, as these are the skills that have been most thoroughly scrutinized across cognitive, behavioural, and biological fields.

### ***Decoding and Reading Comprehension***

Decoding is a crucial skill in young readers that combines phonological awareness and pattern recognition to teach children the phoneme-grapheme conversion between sounds and

script (Facoetti et al., 2010). The efficacy of decoding lies in its procedural repetition and scaffolding off of oral language rules that are already accessible to new readers (Dehaene, 2009). By the time children learn to read they are usually speaking and are familiar with many of the sounds that make up their language(s) (Facoetti et al., 2010). By pairing their knowledge of sounds to the shapes of letters children begin to associate letters and letter combinations (graphemes) with individual phonemes (Smirni et al., 2020). The goal is to teach children the skills to identify both new and familiar words. This is a process that requires heavy attentional allocation – especially in languages such as English with opaque orthographies, for which inconsistent phoneme-grapheme pairings requires children to memorize more spelling rules (Dehaene, 2009; Snowling & Hulme, 2012). Through practice, knowledge of written language becomes more automatic and reading strategies begin to change. Phonological decoding of individual graphemes is parsed out in favour of orthographic decoding (word identification/recognition) of whole words and word combinations based on memorization of word forms and frequency (Dehaene, 2009; Hamilton et al., 2016; Reynolds, 2000). Orthographic decoding allows for faster and more effortless reading of frequently encountered text, while phonological decoding is retained for learning new or difficult words (Pugh et al., 2001).

Unlike decoding, which is simply a reading skill, reading comprehension is the goal of reading – creating a mental representation of written information that conveys meaning. Effective reading comprehension requires the coordination of many different skills; readers must understand individual words through the use of phonological, orthographic, and semantic representations, while also connecting the meaning of entire passages via inferential and referential processing (Kendeou et al., 2014). These demands become more complex over time

as reading material becomes more dense, requiring greater background knowledge and inference making to understand (Hamilton et al., 2016). Reading comprehension relies on underlying skills that fall into two categories; lower level skills that involve translating text into meaningful units, such as phonological decoding, vocabulary, and reading fluency, and higher level skills involved in linguistic comprehension, such as executive functioning, attentional allocation, and inference making (Kendeou et al., 2009; Snowling & Hulme, 2012). As lower level skills become more automatized throughout reading development, reading comprehension becomes disproportionately more dependent on the higher level skills involved in linguistic comprehension (Snowling & Hulme, 2012). However, both sets of skills begin to develop long before formal reading instruction and provide the foundation for reading comprehension across the lifespan (Cervetti et al., 2020; Kendeou et al., 2014; Kim, 2017). Several models have been proposed over the years aimed at identifying how these underlying reading skills develop and interact with one another to create meaningful reading comprehension – as well as what might occur when they do not.

### **Models of Reading Acquisition**

Theories of reading development have evolved over time, building off of self-described ‘simple’ broad statement models to include multiple information streams, and the contribution of domain-general memory, and executive processes. It seems that our understanding of reading has mirrored the reading process itself in that it has built off of component pieces to become increasingly complex over acquisition. In reviewing both past and current models of reading from different fields of study, a strong line of converging evidence begins to grow that better characterizes the decoding to reading comprehension relationship and all components that contribute to it.

### *The Simple View of Reading*

The simple view of reading (Gough & Tunmer, 1986) is currently one of the most widely known models of reading. It suggests that reading comprehension is both developed and predicted by decoding and language comprehension performance in tandem; if a reader can both decode the text they are reading, and understand the words they are decoding, then they will show reading comprehension (Kendeou et al., 2009). There is a wealth of evidence in support of the validity of the simple view of reading and its accuracy in describing reading performance in people with and without RD (Kendeou et al., 2009). However, while the model is comprehensive and broadly accurate it lacks precision. It does not account for how decoding and language comprehension develop independently (Kim, 2017), nor does it adequately account for the independent roles of semantics, episodic memory, strategy monitoring, and motivation within reading comprehension (Cartwright et al., 2016; Cervetti et al., 2020; Connors, 2009). Over the last few decades, the reading literature has sought to develop additional models that accurately represent the intricacies of each reading component.

### *The Dual Route Theory*

The dual route theory of reading is another widely accepted model, this time of reading mechanisms, which are not mutually exclusive from theories regarding the decoding-reading comprehension relationship. This model proposes two cognitive pathways which are used to process text: the fast lexical route through which familiar words are automatically processed, and the slower sublexical route through which unfamiliar or non-words are sounded out phonetically (Pritchard et al., 2012). These routes echo orthographic and phonological decoding respectively, and describe a pathway of reading acquisition that is not just based on effectively using

underlying skills to understand text, but also automatizing the use of those skills over time to make reading an efficient practice (Coltheart et al., 2001).

### *The Dorsal-Ventral Model*

The dorsal-ventral model of reading proposed by Pugh et al. (2001) adds a neuroanatomical aspect to the reading literature, and converges strongly with the dual process model of reading. Evidence from neuroimaging studies suggest that there is a common posterior cortical reading network in the left hemisphere of the brain, and that this network has both dorsal and ventral components, which seem to perform different functions (Richlan et al., 2011). The dorsal components, also known as the temporo-parietal circuit, is involved in the act of slow phonological decoding, which is essential in the early stages of reading when readers are working to build up a lexicon (Pugh et al., 2001). The dorsal circuit is also stated to tax anterior attentional units, such as the inferior frontal gyrus, more heavily (Barquero et al., 2014). Conversely, the ventral components, also known as the occipito-temporal circuit, are most active during tasks of orthographical processing. The ventral circuit acts very quickly and can differentiate between a familiar word and a pseudoword in 150-180ms (Pugh et al., 2001).

The dorsal-ventral model of reading proposes that both dorsal and ventral streams work in tandem during skilled reading, with the ventral circuit activating during fast, low resource, word reading, and the dorsal stream facilitating phonetic decoding of unfamiliar or new words (Pugh et al., 2001). The circuits overlap greatly, such that proper temporo-parietal organization in the dorsal stream is needed for the ventral stream to efficiently process written words as linguistic information (Shaywitz et al., 2002). Without this scaffolding, reading skill grows to rely more heavily on support from right-hemisphere temporo-parietal regions and bilateral frontal

regions rather than exclusively left hemisphere circuits (Chyl et al., 2021; Pugh et al., 2001). The dorsal ventral model of reading is similar to the dual route model, in its breakdown of phonological to orthographic decoding, and the automatization that occurs in that process (Pritchard et al., 2012). However, the dorsal ventral model adds evidence from neuroimaging studies to provide anatomical mechanisms through which slow phonological and fast lexical routes develop (Schlaggar & McCandliss, 2007).

### ***The Attentional Resource Emancipation Model***

The attentional resource emancipation model of reading outlined by Reynolds (2000) addresses cognitive processes such as selective attention and the presence of existing schema that had posed a problem to previous broad sweeping models of reading. Simply speaking, attentional allocation and the preconceived ideas of an individual are both large contributors to the learning process and can greatly affect both reading comprehension, and the strategies one uses while reading (Reynolds, 2000). A culmination of studies conducted at the end of the 20<sup>th</sup> century recognized that previous experience, or existing schema had significant effects on the interpretation and memory recall of text (Bransford & Johnson, 1972; Goetz et al., 1983). Attentional allocation, it was found, had a role to play in the strategies used when deciphering that text (Reynolds, 2000). These findings have been replicated in recent studies as well (Facoetti et al., 2010; Hamilton et al., 2016), and establish the impact that attentional resources and memory can have on both decoding and reading comprehension.

Both good readers and poor readers require attentional resources in reading acquisition, but where good readers focus their attention on identifying the important information within passages, monitoring their reading strategies, and maximizing reading comprehension, poor

readers spend more effort analyzing the structure of the words they read at the expense of reading comprehension (Campen et al., 2018; Reynolds, 2000; Vaughn et al., 2020). This is the basis of the attentional resource emancipation model of reading. This model states that attention is a fixed resource, and that both decoding and reading comprehension require some degree of attentional allocation (Reynolds, 2000). As decoding becomes an automatic process, echoing the movement from phonological to orthographic reading, attentional resources previously used in decoding become ‘freed up’ to facilitate reading comprehension and reading strategy (Reynolds, 2000). However, if attentional resources are inadequate, due to reduced attentional capacity, inefficient allocation of those resources, or inability to reduce the resources used in decoding, reading comprehension will suffer (Reynolds, 2000). Support for this model comes from a variety of studies which have identified working memory capacity to influence reading comprehension more in slow decoders compared to fast decoders in adult readers (Hamilton et al., 2016); that poor attention shifting negatively impacts reading acquisition in children with RD compared to slow but accurate decoders with RD (Facoetti et al., 2010); and that working memory has a significant indirect effect on reading comprehension and word reading efficiency through decoding (Arrington et al., 2014; Campen et al., 2018; Follmer, 2018).

### ***Towards a Consolidated Approach***

The attentional resource emancipation model combines ideas from both the simple view of reading, in that decoding is a necessary precursor to successful reading comprehension, and dual process model, in that slow phonological decoding must make way for more efficient orthographic decoding. Reynolds’ (2000) model adds that it is attentional resources which are the driving factor behind reading development in both the decoding to reading comprehension relationship and the slow to fast decoding relationship. Furthermore, the attentional resource

emancipation model also has strong parallels with Pugh's (2001) dorsal-ventral model, which is anchored in neuroimaging findings rather than purely behavioural measures. To see separate models converge around a single skill – decoding – based on separately defined evidence from both cognitive and biological measurements of that skill suggests a consolidated approach may be best suited to our current understanding of reading development. Recently, just such an approach has been suggested, with Duke and Cartwright's (2021) proposed model, the Active View of Reading. This model suggests a multifactorial system in which decoding/word recognition is tied to reading comprehension through a number of 'bridging processes' identified by previous studies and includes active self-regulation as a independent component which can influence decoding, reading comprehension, and bridging processes (Duke & Cartwright, 2021). Self-regulation includes attention and motivation, as defined through executive function skills, strategy use, and engagement and acknowledges the component of attention to have an essential role in the biological development of reading circuits in the brain as well as the behavioural outcome of reading skill (Duke & Cartwright, 2021). To begin to apply this model, however it must first be understood how attention is defined.

### **Defining Attention in Reading**

#### **Executive Functions**

Executive functions is a broad term referring to a range of cognitive processes that are required for the planning, monitoring, and execution of goal directed behaviours (McCabe et al., 2010). As executive functions are higher order cognitive processes, generally associated at least in part with the frontal lobe, they develop significantly over the course of childhood and adolescence (Goldstein & Naglieri, 2014). Due to their ongoing developmental trajectory,

executive functions have shown to be important predictors of academic achievement in grades from early childhood onward, and have also been evidenced to impact reading outcomes directly (Follmer, 2018; Fuhs et al., 2014).

While there are a great number of executive functions, each with their own definitions that vary and overlap from field to field, there are three core functions which are generally considered separable but also interdependent: shifting, updating, and inhibition (Miyake et al., 2000). Shifting (also referred to as cognitive flexibility) is the ability to switch between multiple tasks, mental sets, or goals; updating is the process of monitoring and coding information in accordance with changing demands over the course of a task; and inhibition is the suppression of automatic or dominant responses in favour of the response that is required to complete a task (Follmer, 2018). Working memory (WM) refers to the process of holding information in mind and manipulating it on a temporary basis (Follmer, 2018). While it is often included within the scope of executive functions WM is unique as it can be considered as the core skill of updating (McCabe et al., 2010; Miyake et al., 2000), or as a model through which all core executive functions may be understood and compartmentalized (Baddeley, 2017; Scharinger et al., 2015). This is largely dependant on the perspective of the individual discussing it.

Attention, or attentional control, is often seen as a necessary component of goal directed behaviour and the common element between all executive functions, however it does not account for all of the variability between them (McCabe et al., 2010; Miyake & Friedman, 2012). As such, there is value in looking at executive functions and their contributions to behaviour both individually and as a collective, but this is most effective when executive functions are

constrained under a single model. This thesis will use the multicomponent model of working memory to define executive functioning.

### **The Multicomponent Model of Working Memory**

The multicomponent model of working memory devised by Baddeley and Hitch (1974) is one of the most widely accepted models of WM. The model consists of four separate subcomponents which aim to better categorize the types of information that can be held in storage and the manner in which they are retrieved and manipulated (Baddeley, 2017). These components are the two subsystems – the phonological loop, visuospatial sketchpad – which represent short term memory stores, the episodic buffer, and the central executive which acts as an attention based controller (Baddeley, 2017).

As the active controlling unit, the central executive is tasked with shifting attention between the two subsystems and utilizing the information they are holding to perform a task. The WM system is both time and capacity limited, such that subsystems cannot passively hold information in memory at indefinite quantities or without degradation over time and must be maintained by the central executive (Baddeley, 2007). The phonological loop stores all auditory and verbal information, while the visuospatial sketchpad stores mental images of objects and their spatial orientation (Baddeley, 2007; Mueller et al., 2003). The episodic buffer, which was added to the model in 2000, temporarily stores information based on familiarity of the material, and may act as an interface between the phonological store and visuospatial sketchpad in this role. It is considered separate from long term memory (Baddeley, 2000). Of these components the phonological loop has been the most thoroughly studied (Baddeley, 2017).

The phonological loop is the subcomponent which temporarily stores auditory and verbal information, including the written word. Like an atom giving way to quarks, the phonological loop can too be broken again into two additional subcomponents: the phonological store and articulatory loop (Baddeley, 2017). The phonological store is the site where all auditory and verbal information is held, while the articulatory loop works as a rehearsal process to prevent the decay of information in the phonological store (Baddeley, 2017). The capacity of the phonological store depends on many variables, including word length, phonological, orthographic, and semantic similarity in word strings, articulatory suppression, and reading rate (Mueller et al., 2003). While some of these variables (e.g., semantic similarity) may primarily depend on the episodic buffer (Baddeley, 2000), many others (e.g., word length, articulatory suppression, and reading rate), depend on the speed and availability through which the articulatory loop recites the information to keep it maintained within the phonological store (Aboitiz et al., 2010; Baddeley, 2017). When storing written information, the articulatory loop acts as an ‘inner voice’ in order to encode text into its phonological representation in the phonological store (Mueller et al., 2003). Evidence for the mechanisms of the phonological loop has been replicated in studies with adults, children, and people with psychological and developmental disorders (Baddeley & Jarrold, 2007; Cogan et al., 2017; Gray et al., 2017; Tam et al., 2010).

The phonological loop differs from the visuospatial sketchpad not just in the modality of the information it holds, but also the way in which it holds it. Phonological information is temporally sensitive and tends to be recalled either serially or in sequential chunks (Zhijian & Cowan, 2005). Visuospatial information on the other hand is not suited to serial recall; here information is held as a single complex pattern in which objects are held in spatial relation to one

another (Baddeley, 2000). Both the phonological loop and visuospatial sketchpad have some capacity to the amount of information that can be passively held in memory at once and require additional resources either from the central executive or episodic buffer to hold additional information. The central executive utilizes active attention to update and maintain information in storage, shift attention between the storage units, and inhibit competing information (Baddeley, 2000; Morey & Cowan, 2005). Active rehearsal and retrieval of information can tax attentional control quite heavily, leading to incorrect recall, impaired reasoning, and loss of retrieval if the memory load is too high or attention is split between multiple tasks (Lavie, 2010; Morey & Cowan, 2005). Importantly, encoding of information through rehearsal may reduce demands on the central executive by committing more information to long-term memory, where it may be retrieved by the episodic buffer at a reduced attentional cost (Baddeley, 2000; Morey & Cowan, 2005; Rudner & Rönnerberg, 2008).

### ***Working Memory or Short-term Memory?***

There remains some controversy on whether the multicomponent model of working memory (Baddeley & Hitch, 1974) is equitable to conceptualizations of short-term memory, such as Atkinson and Shiffrin's (1968) modal model of memory. In a recent review of the modal model of memory, Malmberg et al. (2019) restate that short-term memory was always considered an active process with multiple modalities to store information and control processes to help encode, store, and retrieve information. These components are very similar in nature to the subsystems – the phonological loop and visuospatial sketchpad – and the central executive from the multicomponent model of working memory. Thus, it is apparent that although differences between models exist, the core components of each run in parallel and would be difficult to differentiate empirically (Malmberg et al., 2019). It is important to note that both the

multicomponent model and modal model have seen revisions since their conception that cumulatively build off of new ideas on temporary memory management as cognitive research has advanced (Baddeley, 2017; Malmberg et al., 2019).

### **Working Memory and Reading**

There is a familiar lack of consistency in the executive functioning terminology used in literature regarding attention and reading. In effort to maintain the chosen model of WM while correctly representing the relevant literature, this section will first summarize research focusing on the three core components of executive functioning, with the understanding that the multicomponent model of working memory encompasses part or all of these components within the function of the central executive.

Updating, shifting, and inhibition are strongly involved in several components of the reading process. A recent meta-analysis of 29 studies found executive functions to have a moderate association with reading comprehension, particularly in the age range of 6-17 (Follmer, 2018). This effect was most fully seen through shifting, and updating, as well as planning, which is differentiated from the three core functions in some studies. Deficits in shifting and updating were most often explained through weaknesses in phonological processing and maintaining coherent text representations, while deficits in planning seemed to uniquely contribute to reading comprehension (Cirino et al., 2019; Locascio et al., 2010). Inhibition did not significantly contribute to reading comprehension above the other functions, possibly as a result of the common factor of attentional control which underlies it (Follmer, 2018; Kieffer et al., 2013). In studies looking at single word-reading, there have been mixed results as to the impact of executive functioning. One study found that inhibition and shifting only impacted decoding in

children with RD when they had an accompanying deficit in math ability (van der Sluis et al., 2004), while others have shown poor decoders to have significantly delayed attentional shifting compared to both controls and children with RD who were more accurate decoders (Facoetti et al., 2010).

Arrington et al. (2014) found evidence of WM to be involved in both reading comprehension and decoding, stating that attentional control may function differently within the two reading processes. WM has been seen to have direct effects on both single word decoding and reading comprehension (Campen et al., 2018; Locascio et al., 2010; Vaughn et al., 2020), it has also been found to have an indirect effect on reading comprehension through decoding (Arrington et al., 2014). These findings are mirrored in an article by Chen et al. (2016) who found visual attention – as defined through the visuospatial sketchpad – to have direct effects on pseudoword decoding and reading comprehension independently of phonological awareness in adolescents with RD. Georgiou et al., (2008) found WM to account for some variance in both decoding and reading comprehension, but stressed that the significance of these findings was dependent on whether or not the WM task primarily tapped the central executive over the storage units. Yet another study found the episodic buffer to play a significant role in the development of word recognition skills in children through the binding of visual and phonological information (Wang & Algozzine, 2011). WM has also been suggested as a factor in several other reading components including verbal fluency, inference generations, vocabulary, temporal speech processing, and semantic processing, which can each be considered individual skills that work towards the common goal of reading comprehension (Cirino et al., 2019; Follmer, 2018; Hamilton et al., 2016; Mariën et al., 2014).

By and large, the role of WM in reading has been most thoroughly scrutinized through reading comprehension. This is not without reason. Reading comprehension is both the goal of reading, and the skill that requires the most mental effort, particularly when the text is difficult or when underlying component skills are not properly developed. WM has been repeatedly seen to play a contributing role in reading comprehension which increases with more effortful reading (Follmer, 2018), however it is not yet clear which subcomponents of WM are involved in which reading skills, or if there is a global deficit of WM in those with RD. It is worth looking into concurrent disorders in effort to interpret the literature.

### ***Reading Disorder and ADHD***

Demographically, children with RD are commonly found to have poorer WM than their typically developing peers and a high comorbidity with other developmental disorders such as attention-deficit/hyperactivity disorder (ADHD), math disorders, and speech and language impairment (SLI; D'Mello & Gabrieli, 2018) – this is particularly true of children who are resistant to reading intervention (Cirino et al., 2019; Fletcher et al., 2011). ADHD, which is characterized in part by global deficits in WM capacity and processing speed, has been shown to co-occur with RD at a rate that is far higher than chance. Clinical studies have reported anywhere from 9-60% of children with RD also have ADHD, depending on how each disorder is defined (Sexton et al., 2012). RD and ADHD have been found to have common genetic influences, particularly within traits of inattention and processing speed, as well as shared structural abnormalities over development (Adams et al., 2017; Willcutt et al., 2005). Both disorders are also highly heritable, and this heritability increases with a comorbid presentation, indicating a need to view RD and ADHD not as separate disorders, but as disorders that reflect shared etiology (Willcutt et al., 2007). Understanding of the genetic and behavioural overlap between

RD and ADHD may benefit future studies in their interpretation of cognitive functioning data, as well as best approaches to effective intervention programs.

### **Executive Functions and Reading Models**

Executive functions are often inconsistently defined across different fields of research. The catch all term may be synonymous with attention or WM in one perspective, while attention may be considered a subcomponent of executive functions in another perspective. Through the viewpoint of the attentional resource emancipation model, attention refers to correctly identifying important information within a text, using text based cues to direct information gathering, monitoring reading strategies for their effectiveness, and the ability to alter that strategy when it is not working efficiently (Reynolds, 2000) – all processes identified under the active self regulation component proposed in the Active View of Reading (Duke & Cartwright, 2021). It may be argued that the skills referred to in these models mirror the three core executive functions in application – or attentional control the common factor that underlies all executive functions. This thesis will take the perspective that the role attention outlined in these models can be explained through the multicomponent model of working memory.

Taken individually each application of attention outlined by Reynolds (2001) describes the central executive's role in monitoring its subsystems and manipulating the information held in each. Provided the storage systems are within their capacity during a task, the central executive should be able to facilitate attention and reasoning simultaneously. However, when storage subcomponents are limited they must call upon the central executive to help maintain information, at the cost of reasoning (Baddeley, 2017). This is the basis of the attentional resource emancipation model, which states that attentional resources that would normally be

allocated to reading comprehension must instead support decoding if the earlier skill has not been sufficiently automatized (Reynolds, 2000). Duke and Cartwright's active view of reading further facilitates this theory by identifying bridging processes between decoding and reading comprehension that can be independently influenced by executive function skills, motivation, and strategy use (2021). Single word decoding starts out as a slow skill which requires a great deal of attentional resources to break down each word phonetically (Dehaene, 2009). As early readers move from phonological to orthographic decoding they are able to utilize the articulatory loop and episodic buffer through bridging skills such as vocabulary and morphological awareness to maintain more information without active processing by the central executive (Morey & Cowan, 2005). This frees up more attentional resources for reading comprehension – which becomes increasingly important as reading demands get heavier in later grades (Connors, 2009). In the case of RD, failure to allocate attention appropriately may be due to either reduced capacity of the phonological loop resulting in a central executive that must split its active processing between decoding and reading comprehension, or reduced capability of the central executive which may directly deficit the learning process of both decoding and reading comprehension as a whole (Fletcher et al., 2011).

The multicomponent model of working memory is both well established within the cognitive literature and strongly compliments the attentional resource emancipation and active view of reading models with its central executive as the active allocator of attention that helps to facilitate both early and late reading skills. Moreover, the multicomponent model has been widely referenced in research identifying areas of the brain associated with WM in neuroimaging studies (Emch et al., 2019; Nee et al., 2013; Rottschy et al., 2012; Thomason et al., 2009). In considering the role of attention in reading development, WM as defined through the

multicomponent model purports itself as a particularly influential factor that is relevant to both cognitive and biological research.

## **The Biological View of Reading**

### **The Reading Network**

Although reading is a complex learned behaviour that draws on a range of subsidiary skills, the broad network through which it is thought to operate has remained largely consistent across the literature. Concerning the typically developed population, skilled reading is left lateralized in the brain with three broad areas of function; the temporo-parietal region, the occipito-temporal region and the inferior frontal cortex – these areas are also referred to as the dorsal posterior, ventral posterior, and anterior regions in some contexts (D’Mello & Gabrieli, 2018).

The temporo-parietal region contains the inferior parietal lobule (IPL) including the supramarginal gyrus and angular gyrus, as well as the superior and middle temporal gyri (STG; MTG) and is involved in phonological and semantic processing (Barquero et al., 2014; Paulesu et al., 2014). It is the same region that comprises the dorsal stream outlined in Pugh et al.’s (2001) dorsal-ventral model of reading, and as such is the slower processing region that integrates orthographic information with phonological representations to phonologically decode words. The temporo-parietal region is also thought to play a part in rule-based analysis involved in lexical semantics and grammar (D’Mello & Gabrieli, 2018). The occipito-temporal region consists of the fusiform gyrus, sometimes termed the visual word form area (VWFA), and acts as the automatic visual processing unit that orthographically decodes words or strings of text as

whole (Barquero et al., 2014). In conjunction with the dorsal-ventral model it acts as the fast ventral stream which automatically decodes familiar words without phonological processing (Pugh et al., 2001). Finally, the interior frontal cortex primarily consists of the inferior frontal gyrus (IFG), with some studies also focusing on the insula and precentral gyrus (Aboud et al., 2018; Barquero et al., 2014). This region is thought to be involved in phonological processing as well, with a focus on articulatory recoding, due to the known role of the IFG in speech-motor production, semantic processing, and verbal WM (Barquero et al., 2014; D’Mello & Gabrieli, 2018). In accordance with the dorsal-ventral model the anterior region is thought to support the dorsal region in phonological decoding, particularly during early reading or when a reading task is at a level of difficulty that requires additional articulatory recoding to process (Pugh et al., 2001).

### ***Reading in the Developing Brain***

As suggested by the dorsal-ventral model, neuroimaging evidence has shown the reading network to shift considerably over the course of development. Though all three regions are involved in reading from the onset of the skill, the contribution of each region to the process of reading changes depending on the level of experience the reader has (Richlan et al., 2011). Over typical reading development there is an overall decrease in reading network activity regardless of reading outcome. However, greater decreases in temporo-parietal activity over occipito-temporal activity is significantly associated with better reading outcomes (Wise Younger et al., 2017). Increased grey matter volumes in dorsal and ventral regions during childhood has been found to predict for overall reading ability as well as for subskills in phonological processing and rapid naming (Hoefl et al., 2011).

Comparisons between adult and child readers have found that children typically have higher levels of activity in regions that process phonological data, particularly within the IPL (Barquero et al., 2014). The left supplementary motor area, left superior temporal cortex, and left middle frontal cortex have all been identified to have child-specific activity as well, perhaps accounting for the recruitment of attention and speech processing regions during learning (Paulesu et al., 2014). Activity in the occipito-temporal gyrus during reading has been found in children as young as six, but only among those without reading difficulties (Richlan et al., 2011). Increases in inferior frontal cortex activity is most commonly associated with weak reading skills in later childhood (Pugh et al., 2001).

In conjunction with evidence found from activity-based analyses, studies using functional connectivity have identified several notable differences over the course of reading development. Globally, developmental increases in white matter connections across the reading network has been positively associated with reading ability, with stronger connectivity between the dorsal and ventral regions in childhood predicting for better reading outcomes compared to peers (D'Mello & Gabrieli, 2018; Wise Younger et al., 2017). High improving readers show a decrease in dorsal connectivity over time and maintain their ventral connections compared to low improving readers, accounting for the decreased reliance on the dorsal circuit as their skill in automatic word recognition grows (Wise Younger et al., 2017). Younger readers show increased connectivity between the left IFG and left middle frontal cortex which decreases over time and is thought to mediate attention to visual stimuli in early reading. Older readers by comparison, show a stronger connection between the left IPL, the left middle frontal cortex and bilateral superior prefrontal cortex, which is evidence of a matured top-down application of attention on visual stimuli (Finn et al., 2014). Similarly, connections between the left IFG and fusiform gyrus

have been shown to decrease over the span of 2-3 years in typically developing children, while connections between the left IFG and IPL increase (Wise Younger et al., 2017). Finally, left-lateralization of the reading network has also been seen to increase over the course of development, but whether this is due to the natural development of language processing regions as a whole, or significantly influenced by reading experience in typically developing readers remains to be seen (Weiss-Croft & Baldeweg, 2015).

### ***Development of the Reading Network in Reading Disorder***

Development of the reading network in people with RD differs from typical development in a number of ways. Overall, there is a reduction of grey matter volume, and white matter connectivity across the reading network in children with RD, with weaker left hemisphere activity during reading (D’Mello & Gabrieli, 2018). These differences have even been found in pre-reading children and infants suggesting that they are not a result of a failure to read (D’Mello & Gabrieli, 2018; Vandermosten et al., 2016). Differences in network activity take a distinct pattern, with multiple reviews citing reduced activity within the temporo-parietal and occipito-temporal regions at large and overactivity in the IFG (Barquero et al., 2014; Richlan et al., 2011). Reduced and altered connectivity of the VWFA has been reported, as well as under activation in response to word based stimuli and a lowered sensitivity in identifying real words vs pseudowords (D’Mello & Gabrieli, 2018; Finn et al., 2014). However, a meta-analysis comparing child and adult studies found that reduced occipito-temporal activation was only seen in the anterior segment of the region in child populations (Richlan et al., 2011). Reports of activity in dorsal regions has also been variable in child populations, as some studies identify significant under-activity in the STG and IPL, while others only observe this pattern in adult populations (Richlan et al., 2011). More consistently, reduced left lateralization of the reading

network has been frequently reported, with RD children learning to rely on more of a bilateral structure over development (Finn et al., 2014). This bilateral network can act beneficially as stronger right hemisphere connectivity has been associated with greater improvements over reading intervention in children with a family history of RD (Hoeft et al., 2011). Typical tasks used in identifying group differences in the reading network include rhyme matching, phoneme matching, pseudoword and word reading, sound deletion, and spelling judgement tasks (Barquero et al., 2014).

Alternate connectivity and development of the IFG is one of the most commonly reported findings when comparing children with RD to their typically developing counterparts. Generally overactivation of the left IFG is reported in RD populations across age groups (D'Mello & Gabrieli, 2018), however emerging evidence comparing child and adult studies of RD found under-activation in the left IFG in children compared to adults in two out of six studies (Richlan et al., 2011). Overactivation in the left IFG is thought to be due to compensatory processes, in which the anterior system is helping to support the dorsal system through either increased attention from the central executive, or the articulatory loop (Barquero et al., 2014). If this is the case, it is interesting that Richlan et al. (2011) found under-activation of the left IFG in child populations in some studies, however they do note that the precentral gyrus saw over-activity which was not seen in the adult studies. The precentral gyrus lies across the posterior end of the frontal lobe, behind the frontal gyri, and has been associated with Broca's aphasia in lesion studies, suggesting that it may participate in subvocal rehearsal alongside the IFG (Mori et al., 1989). Significant differences in the functional connectivity of the left IFG to the left precentral gyrus, right and left supplementary motor area, and right superior and inferior frontal gyri has been found between children with and without RD, further suggesting that alternative

compensatory pathways may be in use during reading tasks (Richards & Berninger, 2008).

Activity in the right IFG, as well as connectivity between the right and left IFG, is mainly increased in RD children when compared to typically developing controls; this finding remains regardless of the child's reading ability, though in persistently poor readers lower levels of activation is observed compared to RD children who were receptive to intervention (Hoeft et al., 2011).

### **Working Memory and the Reading Network**

While the exact neural sites of the WM network are not yet fully differentiated, results from several meta-analyses and literature reviews in the recent past have identified key regions that overlap between the currently defined WM network and reading network (Arrington et al., 2019; Emch et al., 2019; Owen et al., 2005). Most notably, reviews have successfully differentiated task dependent WM activity for both verbal and non-verbal stimuli. According to one meta-analysis of 189 fMRI studies on WM, tasks that used verbal stimuli (whether auditory or visual) were far more likely to recruit the left inferior frontal gyrus (IFG), particularly within the triangularis and opercularis subregions (Rottschy et al., 2012). These areas correspond with Brodmann areas 44/45, which have been well established for their association with language, including the processing of both phonology and semantics, as well as speech production (Müller & Knight, 2006). Similarly, in studies that utilized non-verbal WM tasks, activation tended towards higher convergence in the left supplementary motor area (SMA) and bilateral dorsal pre-motor cortex (dPMC), with the latter active *only* for non-verbal over verbal tasks (Rottschy et al., 2012). Both the left SMA and dPMC are known to be involved in the planning of spatial and motor movements. The SMA has been suggested to play a partial role in the planning and initiation of complex movement sequences, as well as peripheral attention (Kelley et al., 2008),

while the dPMC has shown evidence towards the initiation of simple movements, and task switching (Hoshi & Tanji, 2007).

Representing persistent main effects of WM are the anterior and parietal regions that make up the central executive network – the middle frontal gyrus (MFG), rostral prefrontal cortex (rPFC), and intraparietal sulcus (IPS). Each of these regions are more persistently activated in studies that utilize N-back memory tests over Sternberg tests (Rottschy et al., 2012). N-back tests strongly task WM load as well as active manipulation of information, whereas Sternberg tests assess storage and retrieval. Activation of the central executive network is persistent across both verbal and non-verbal stimuli in tasks that involve manipulation of object identity and location, suggesting these regions play a role in planning and attentional allocation over information storage (Owen et al., 2005). Activation in the bilateral IPS and left rPFC had a higher association with the initiation of WM, while the bilateral MFG and right rPFC showed more convergence with increases in WM load. (Rottschy et al., 2012).

It has been suggested several times that the IFG opercularis and triangularis regions may correspond with Baddeley's phonological loop, due to their observed activation in both the passive recall and active rehearsal of verbal information (Rottschy et al., 2012). Once again, this effect is seen in the left IFG regardless of whether the verbal stimulus is auditory or visual (Malins et al., 2016), which further corresponds with Baddeley's proposed model. If this is the case, Rottschy et al. (2012) suggest that the left SMA and bilateral dPMC may similarly correspond to the visuospatial sketchpad, while the IPS may take on a multi-modal role corresponding with both verbal and non-verbal frontal sites. A conflicting meta-analysis only partially agrees with these ideas, finding the left IFG to indeed be associated with the

phonological loop, but arguing that the left SMA plays the part of the articulatory loop as well (Emch et al., 2019). In this meta-analysis the left SMA was found to have higher convergence on tasks that required subvocal rehearsal, while the right SMA, right IFG, and subthalamic nucleus were active during go/no go tasks to inhibit competing responses (Emch et al., 2019). These findings may speak more to the phonological loop and central executive than they do the visuospatial sketchpad. However, it is worth noting that this meta-analysis included only studies that recruited verbal WM, and therefore did not compare verbal and non-verbal activity.

Emch et al. (2019) also advocate for the role of the cerebellum in verbal WM tasks, and found significant activity within lobule VI/Crus I in their analysis. The cerebellum has been indicated for its involvement in both language and verbal WM skills, including subvocal rehearsal, phonological storage, and verbal fluency (Mariën et al., 2014). Previous meta-analyses also cite significant activity in lobule VI of the cerebellum, but note that this was only seen in the main effect and not for specific verbal or non-verbal tasks (Owen et al., 2005; Rottschy et al., 2012).

### ***Defining the Overlap Between Reading and Working Memory Networks***

Although the reading network has been well defined as its own distinct bundle of left lateralized anterior, parietal, and ventral regions, it has significant overlap with verbal, non-verbal, and centralized regions in the WM network. This is particularly salient in younger readers who show higher activity in dorsal posterior and anterior regions while they are learning and those with RD who maintain higher anterior activity throughout development (D'Mello & Gabrieli, 2018; Pugh et al., 2001). Child specific activity during both reading and non-reading WM tasks is prevalent in the left SMA, left IFG, and left MFG, while the right IFG, middle

frontal cortex, and superior frontal cortex all see connectivity changes over the course of reading acquisition (Paulesu et al., 2014). Likewise, children with RD see reduced lateralization of the reading network as well as further functional differences in the right and left IFG, as well as the inferior parietal lobule which lies just ventral to the IPS (Hoeft et al., 2011; Zhou et al., 2015). Taken together it becomes evident to suggest the WM network may be critical in the early reading process – an idea which is reinforced by the dorsal-ventral model, the attentional resource emancipation model, and the active view of reading.

### **Research and Rationale**

Several converging theories suggest a role for WM in early reading skills, and stress that failure to appropriately gain these reading skills can result in poorer reading comprehension across age groups (Follmer, 2018). Likewise, studies using neuroimaging have shown distinct developmental differences in both reading and WM networks can occur early in childhood and may predict reading outcome (Aboud et al., 2018; Hoeft et al., 2011; Nugiel et al., 2019). However, when it comes to directly observing the effects of WM on early reading skills, the research becomes scarce and often contradictory. There is a lack of clarity regarding the contribution of WM components to early reading components, and mixed evidence suggests that it is as of yet unclear whether RD is associated with a global WM deficit or a WM deficit that is specific to the verbal domain only (Fischbach et al., 2014; Georgiou et al., 2008). This is due in part to the observed overlap between WM and reading measures, which make it difficult to see the specific contribution of WM to most reading skills (Aboud et al., 2018). Functional neuroimaging measures may be a more appropriate method to observe WM in early reading development (Beneventi et al., 2010), but few functional neuroimaging studies exist that have assessed WM during a simple single word reading activity.

This study bases itself off evidence that WM is necessary during single word decoding that requires activation of the dorsal circuit to a greater extent than word reading that utilizes the ventral circuit (Chyl et al., 2021; Schlaggar & McCandliss, 2007). If this is the case, introduction of a memory task during reading that requires active judgement of verbal material should necessitate a greater recruitment of WM similar to what is seen during phonological decoding. For example, a task comparing passive reading trials with n-back trials could create just such an effect, requiring participants to scrutinize words and pseudowords through slower processing streams (Arrington et al., 2019). Based on Baddeley's multicomponent model of working memory (1974) and subsequent studies on WM capacity, words that are more difficult to interpret should require higher activation of the WM network as the central executive splits attentional resources between the 'slow' phonological decoding of words and the equally active judgement task. If this is the case, it should be possible to functionally measure WM changes in early reading development with a simple subtraction paradigm. WM activity during single word decoding, may have a higher potential to predict for reading outcomes than previous studies using behavioural measures of WM. This study aims to establish whether or not WM is recruited in single word decoding depending on the reading skill of participants as well as when decoding words, pseudowords, and non-words (false font).

### **Research Questions**

This study addresses four questions pertaining to the functional measurement of WM during single word reading as well as the differences that exist in RD and typically developing (TD) populations at the elementary grade level:

1. Can an fMRI task which compares passive reading trials to n-back trials reliably measure activity in the WM network in children with and without RD (aged 7-9)?
2. How does WM network activity differ for RD and TD populations across words, pseudowords, and false font stimuli?
3. Do verbal and non-verbal stimuli activate different regions in the WM network during an active reading task?
4. Do behavioural measures for verbal working memory or task performance correlate to the functional activity found in the working memory network across both RD and TD groups?

It was hypothesized that addition of an active reading task paired with a passive reading task would recruit the WM network in elementary age readers. However, this recruitment was expected to be dependent on the familiarity of words, such that verbal unfamiliar and non-verbal stimuli resulted in higher WM activity. Similarly, the RD group was expected to have higher WM activity during both word and pseudoword conditions compared to the TD group in accordance with Reynolds' (2000), Pugh et al.'s (2001), and Baddeley's (1974) models of reading/verbal WM. As the RD group was expected to utilize the dorsal/anterior circuits more during word reading – a result of ineffectively maintaining verbal information in the phonological store – addition of a judgement call during reading was expected to necessitate increased reliance on the WM network above that which was seen in the TD group.

The comparison of WM activation in response to verbal and non-verbal stimuli was included in this study in effort to better understand which modalities of WM are altered between RD and TD groups during reading. While some research has suggested those with RD show

deficits in visual WM processes involved in reading (Chen et al., 2016; Wang & Algozzine, 2011), verbal WM deficits appear to be more robust across RD populations (Follmer, 2018). This study predicted verbal WM would have greater differences in functional activity between RD and TD groups. Likewise, it was expected that verbal stimuli would elicit more functional activation in the left inferior frontal gyrus, which has been defined as a predominant area for verbal WM, and that non-verbal stimuli would prompt more activation in the left dorsal premotor cortex and bilateral supplementary motor area – defined as predominant areas for visual WM (Emch et al., 2019; Rottschy et al., 2012).

Finally, exploratory analysis of the correlations between functional activity in the WM network and behavioural measures for WM was included to add context to functional differences seen between groups or stimuli in the WM network. If WM activity was reliably measured within the study, it was suggested correlational evidence between functional activity and behavioural measures of verbal WM may indicate some behavioural metrics of interest for future studies observing WM in early reading skills.

## **Methods**

### **Participants**

Participants were included as part of a larger study conducted in Atlanta, Georgia in an effort to understand the cognitive bases of treatment response in elementary school children with RD. The study was based around a 70-hour reading intervention with behavioural data taken across four timepoints and neuroimaging data taken across two timepoints to assess metrics of intervention response including age, comorbidities, behavioural responses, and

neurodevelopmental trajectories. A total of 168 participants were recruited from elementary schools in the greater Atlanta area. At the first timepoint of data collection, participants were halfway through either the 3<sup>rd</sup> or 4<sup>th</sup> grade. The average age of participants was 9.3 years (min = 7.8, max = 11.3).

The study was approved by the Georgia State University/Georgia Tech Institutional Review Board. All parents and participants provided informed consent/assent prior to the study. Children with reading difficulties were referred to the study through their schools and were classified in the study as having a reading disorder if they achieved a standard score below 85 (1 SD below) on any one of the following reading composites: the Woodcock Johnson III (WJ3), the Test of Word Reading Efficiency – Second Edition (TOWRE-2), and the Scholastic Reading Inventory – Second Edition (SRI2). To control for intellectual disabilities, all participants had a standard score  $\geq 80$  for verbal and performance intelligence using the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II). Any participants with other serious neurological, emotional, or psychiatric conditions were similarly excluded.

Included in this sub-study are the 99 participants (56 male, 43 female) who had complete behavioural and fMRI data at the first timepoint of the study. Participants were divided into one of two groups based on the presence of a reading disorder, with 77 participants classified within the reading disorder group (RD) and 22 participants classified within the typically developing group (TD). Groups did not differ in the distribution of age or gender. However, group differences were found in the WASI-II matrix reasoning subtest as well as NEPSY-II auditory attention scores, such that the RD group had a lower performance than the TD group in both. Children were further assessed for ADHD (n = 31) and/or specific language impairments (SLI; n

= 19) that commonly co-occur with RD. ADHD was assessed via a significant impairment rating on either the Parent/Teacher Disruptive Behaviour Rating Scale (DBRS) or Strengths and Weaknesses of Attention-Deficit/Hyperactivity Disorder Symptoms and Normal Behaviour Scale (SWAN), while SLI was assessed via Tomblin SLI definition. Participants with these two commonly co-occurring conditions to RD were not excluded from the study to better reflect the variability that naturally occurs in this population. None of the typically developing controls met criteria for either ADHD or SLI.

## **Imaging and Task Protocol**

### ***Image Acquisition***

Images were gathered at the GaTech Center for Advanced Brain Imaging in Atlanta Georgia using a 3 T Siemens Trio Scanner with 12-channel head coil at both timepoints. T2\*-weighted images were collected in an axial-oblique orientation parallel to the intercommissural line (32 slices; 4mm slice thickness; no gap) using single-shot echo planar imaging (matrix size = 64 x 64; voxel size 3.438 x 3.438 x 4mm; FoV = 220mm; TR = 2000ms; TE = 30ms; flip angle = 80°). The first six volumes of each run were discarded to allow for the stabilization of the magnetic field. Time between trial onset was jittered between 4 and 13 seconds across all trials in the study. Each participant completed two to four runs of the functional task, with four runs being the optimal outcome. Each run was 316 seconds in duration (158 volumes) for a maximum of 21 minutes of imaging time. 86 Participants completed all four runs, while 11 completed three runs and 8 completed two runs due to issues of timing or participant discomfort. Anatomical scans were collected either between or following functional runs in the same orientation (MPRAGE; matrix size = 256 × 256; voxel size = 1 × 1 × 1mm; FoV = 256mm; TR = 2530ms;

TE = 2.77ms; flip angle = 7°). Imaging data were excluded if they did not meet quality control thresholds, most often due to excessive movement.

### ***Reading/Attention Task***

Participants completed a “fast” localiser reading task with a randomized 1-back trial to assess attention simultaneously (FastLoc–R/A). Within the task, participants were presented with 48 four item trials. In each trial, items were presented one after the other in rapid fashion replicating a passive reading/listening experience. Participants were instructed to press a button with their right thumb if the fourth item in the trial was a repetition of the third. These 1-back trials, which require active assessment of the items being read occurred in 30% of trials across all stimulus conditions. (Arrington et al., 2019). No response was required during the standard reading trials which occurred in the remaining 70% of trials.

There were eight stimulus conditions present in the total study, two auditory conditions and six visual conditions. The current study used data from three of the six visual conditions: unrelated words, pseudowords, and false font. The unrelated word type condition was determined as words that did not share in orthography, phonology, or semantics; all stimuli were balanced for length, frequency, bigram frequency, and deemed familiar for children (Malins et al., 2016). The pseudoword stimuli were created via the MCWord database and matched the word type conditions in length. The false font condition was created using Wingdings font and were matched in length to the pseudoword condition (Malins et al., 2016). Visual stimuli occurred in tetrads, with each item appearing alone on screen for 300ms followed by an ISI of 150ms (Figure 1). Across 4 runs of 48 trials each there was a maximum of 24 trials for each of the 8 stimulus conditions (Arrington et al., 2019).

Button presses in response to trial type were recorded to create a behavioural measure of performance accuracy. Four different response types were possible. 1) Hits: 1-back trials in which the participant correctly responded between 250-2500ms after onset of the target stimulus. 2) Correct Rejections: standard trials in which the participant did not respond with a button press. 3) Errors of omission: 1-back trials in which the participant failed to respond or responded with a latency above 2500ms. 4) Errors of commission: standard trials in which participants incorrectly responded, and 1-back trials in which participants responded with a latency of less than 250ms (Arrington et al., 2019). Mean accuracy was calculated for each participant by comparing the number of hits and correct rejections over the total number of trials completed. Performance accuracy was measured for each stimulus type individually as well as for the task as a whole.

**Figure 1:**

*FastLoc-R/A Trials*

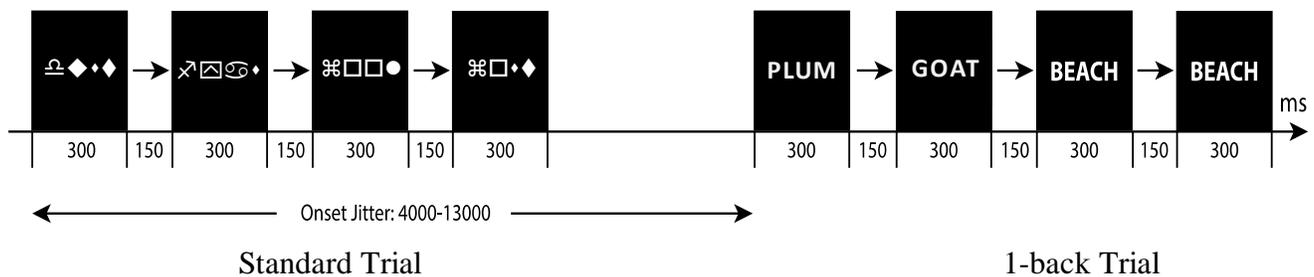


Illustration of a standard reading trial in the false font condition followed by a 1-back trial in the unrelated word condition. (Arrington et al., 2019).

**Data Processing**

Imaging data were processed using AFNI (Cox, 1996) for preprocessing, single subject modelling, and ROI extraction. In preprocessing, the first six volumes in every run were discarded (*3dTcat*) to account for standard stabilization of the magnetic field, and data was

corrected for slice-scan time (*3dTshift*). Next, data were co-registered with anatomical data using the cost function *lpc+zz* and transformed to the Haskins pediatric template by a non-linear warp (*@SSwarper*). The Haskins pediatric template was chosen over the MNI pediatric template as it was found to have a lower non-linear deformation distance in the current subject group. Motion correction was performed by aligning each volume with its minimum outlier fraction (*3dvolreg*). Finally, images were smoothed using a Gaussian kernel with a FWHM of 8mm (*3dmerge*) and scaled to percent signal change such that values in excess of 200 were clipped (*3dcalc*).

Single subject data then underwent a GLM analysis with regressors for correct 1-back trials and correct standard trials for each of the eight stimulus conditions, as well as nuisance regressors for the six motion parameters. In addition, incorrect 1-back and standard trials were considered invalid and modeled with a single regressor. A general least squares time series was used to fit the regression with a restricted maximum likelihood estimation of the temporal auto-correlation structure (*3dREMLfit*). Any volumes exceeding the thresholds of 10% outlier voxels or 0.3mm Euclidian movement were censored.

### ***A-priori ROI Extraction***

Following single subject and group level corrections *a priori* ROIs were extracted from a coordinate based meta-analysis (Rottschy et al., 2012) to represent the WM network. The meta-analysis identified main effect WM via peaks of convergent activation across 189 fMRI studies with a primary WM task, then further compared regional activation between verbal and non-verbal material, task-set and load-dependent effects, and simple recall vs matching and replication (Rottschy et al., 2012). Seventeen ROI coordinates were chosen to best reflect the WM network with consideration to main effect, verbal specific, and visual specific regions. Peak

coordinates were transformed from MNI to Haskins Pediatric space in AFNI (*3dNWarpXYZ*) and used to create spherical ROIs with a centered 6mm radius (*3dUndump*). Beta values were extracted for all participants using *3dROIstats* such that each value represented the voxel average across the ROI. Values were extracted for correct standard and 1-back trials across three stimulus types, false font, pseudoword, and words unrelated in phonology, orthography, or semantics.

Anterior ROIs included the inferior frontal gyrus, the middle frontal gyrus, and the rostral prefrontal cortex, each of which are associated with main effect activation in WM as well as load dependent effects. The left IFG is also considered highly sensitive to verbal stimuli over non-verbal. Likewise, the supplementary motor area and the dorsal premotor cortex were chosen for their specific association with non-verbal WM. Parietal ROIs consisted of the intraparietal sulcus as well as the superior parietal lobule. The IPS represents part of the central executive network with the MFG and rPFC, while the SPL is more commonly associated as part of the dorsal stream. Finally, the right cerebellum lobule VI/VIIa/CrusI was included as another representative main effect activation for its specific associations with the articulatory loop. Both left and right coordinates for identified regions were chosen when available from Rottschy et al. (2012)'s meta-analysis to account for the reduced left lateralization expected from a younger subject group with a high percentage of RD participants. In cases where two peaks of activation for an anatomical region were identified, both were made into individual ROIs as no anatomical overlap was detected after creating spherical activation maps.

**Table 1:***Regions of Interest in the Working Memory Network*

Region	Cytoarchitectonic location		Haskins pediatric coordinates		
			X	Y	Z
L. inferior frontal gyrus	IFG	BA 45	-42	12	27
L. middle frontal gyrus	MFG	BA 46	-46	26	24
L. rostral prefrontal cortex	rPFC	BA 10	-38	50	10
L. supplementary motor area	SMA		-2	19	41
L. dorsal premotor cortex	dPMC		-29	0	49
L. intraparietal sulcus	IPS	BA 40/h1P3	-38	-36	45
L. superior parietal lobule <sup>a</sup>	SPLa	BA 7/7PC	-30	-48	46
L. superior parietal lobule <sup>b</sup>	SPLb	BA 7/7A	-22	-61	49
R. inferior frontal gyrus	IFG	BA 45	46	14	24
R. middle frontal gyrus	MFG	BA 9	44	34	32
R. rostral prefrontal cortex	rPFC	BA 10	38	54	6
R. supplementary motor area	SMA		4	21	41
R. dorsal premotor cortex	dPMC		26	3	49
R. intraparietal sulcus <sup>a</sup>	IPSa	h1P2	37	-43	41
R. intraparietal sulcus <sup>b</sup>	IP Sb	h1P3	29	-55	42
R. superior parietal lobule	SPL	7P	15	-62	50
R. cerebellum	CrusI	lobule VI/VIIa Crus I	28	-62	-11

<sup>a,b</sup>regions with multiple peaks of activation listed under the same anatomical region.

Coordinates given in lpi orientation

### California Verbal Learning Test – Children’s Version

The California Verbal Learning Test – Children’s version (CVLT-C) is a commonly used measure of verbal learning and memory abilities through the components of encoding and rehearsal, memory storage, and memory rehearsal (Fine & Delis, 2018). The test places demands on both memory and executive functions, as encoding and rehearsal require short-term memory,

while memory storage and retrieval assist the recall of learned material (Cutting et al., 2003; Riggall, 2020). Verbal learning and memory strongly relate to early reading skills such as phonological decoding, semantic learning, and word form learning (Riggall, 2020), making the CVLT-C a suitable choice to measure the unique contribution of WM to single word decoding through behavioural metrics.

Previous research has identified WM to significantly contribute to encoding and main memory scores on the CVLT- Second Edition (CVLT-II) in adults with and without ADHD, such that participants with ADHD scored lower on measures for all three components (Lundervold et al., 2019). However it should be noted, that when response inhibition was controlled for, the unique contribution of WM was limited to encoding and memory recall measures only (Lundervold et al., 2019). Similarly, a study on children (aged 6-16) found measures of memory recall from the CVLT-C to be significantly lower in children with ADHD without RD compared to a control group (Cutting et al., 2003). Neuroimaging research has identified use of semantic clustering strategies during encoding and memory retrieval on CVLT tests to be associated with grey matter volume in the left IFG and bilateral MFG (Kirchhoff et al., 2014). The use of semantic clustering strategy training during encoding and retrieval has further been associated with functional activity increases in the bilateral IFG and MFG in healthy adults (Miotto et al., 2006), the left frontoparietal network including the IFG, MFG, dPMC, and IPS in elderly participants with mild cognitive impairment (Balardin et al., 2015), and the right IFG, MFG, and rPFC in adolescents (Miotto et al., 2020). Children were not found to have any significant associations between semantic clustering strategy and the frontoparietal network after memory training in one study, however their verbal recall performance did not improve after training in this study either (Miotto et al., 2006).

The CVLT-C pairs word list learning and recall to assess the encoding, storage and retrieval processes of verbal information at a level that is appropriate for children from the ages of 5 to 16 (Fine & Delis, 2018). During learning trials, participants are presented with a list of words to memorize (List A) and then asked to recall the words on List A in order after each trial (free recall). Five repetitions of List A learning trials test word learning through rehearsal, while intermittent inclusion of an interference list (List B) which shares some semantic commonality with the words on List A tests encoding and short term storage after intrusion (Fine & Delis, 2018). Following the learning period recall of List A is measured after short, medium, and long delay periods, with the long delay being 20 minutes. Recall is tested through both free recall, which relies entirely on the participants storage and retrieval, and cued recall in which the participant is given prompts for the word list based on semantic groupings (Fine & Delis, 2018).

Previous exploratory factor analysis has revealed the CVLT-C to have a three factor internal structure for elementary school children with RD (Riggall, 2020). The current study used the primary loading variables of those three factors as cognitive correlates of verbal WM. These variables were percent recall consistency which was the main contributor to the executive functioning factor, long delay cued recall and recognition hits which equally contributed the most to the verbal memory factor, and total intrusions and false positives which contributed to the inaccurate recall factor (Riggall, 2020). Percent recall consistency is measured as the number of words from List A which are recalled consistently across all five learning trials. Long delay cued recall is defined as the number of List A words a child can remember after a 20 minute delay, while recognition hits defines the number of words a child can correctly identify as belonging to List A while interference words from List B are present. Finally, false positives and total intrusions are the number of words incorrectly identified as belonging to List A after delay,

and during learning trials respectively (Fine & Delis, 2018). Measures within the CVLT-C that did not contribute to these three factors were considered secondarily.

### **Analysis Approach**

Given the scope of the project, this study focused on the behavioural and functional data taken at the very first timepoint before intervention was implemented. By focusing only on pre-intervention data, rather than changes over the course of intervention, this study aimed to establish a baseline to observe functional differences in the WM network between RD and TD children. WM activity within the FastLoc reading task was isolated by subtracting standard trial activity from 1-back trial activity. After subtraction, ROI values significantly above 0 represented an increase in activity in 1-back trials compared to standard trials, while ROI values significantly below 0 represented a decrease in 1-back trial activity in comparison to standard trials. All other values were deemed not significantly active, meaning participants had no identifiable difference in BOLD activity between the two trial types.

## **Results**

### **Main Effects by ROI and Subject Group**

Data were analyzed using IBM SPSS Statistics 28.0 to test for assumptions of normality and identify outliers. ROI values in standard trials were subtracted from ROI values in 1-back trials to isolate the change in activity due to the addition of a judgement task. A series of two-way repeated measures analysis of variance (ANOVA) comparisons were made to assess activity across ROIs and subject group for each of the three stimulus conditions (false font, pseudoword, and unrelated word). ROIs were split by hemisphere to account for loss of power due to the

relatively small sample size resulting in three 2x8 repeated measure ANOVAs in the left hemisphere and three 2x9 repeated measure ANOVAs in the right hemisphere. Analysis found a significant main effect of study group on activity in the false font condition in the left hemisphere [ $F(1,97) = 4.110, p = .045$ ], and in the right hemisphere [ $F(1,97) = 5.011, p = .027$ ] and no main effects of ROI differences, indicating that differences in activity across RD and TD groups were maintained across ROIs in each hemisphere. No significant main effects were found in either hemisphere in the pseudoword condition between study groups or within ROIs. Significant interaction effects between ROIs and study group were found in the unrelated word condition in the left hemisphere [ $F(5.548, 538.201) = 2.281, p = .039$ ] and right hemisphere [ $F(5.626, 545.725) = 2.381, p = .026$ ]. Pairwise comparisons revealed this effect to be largely driven by overactivity of the right and left SMA in the RD group, as well as by underactivity of the right rPFC in the TD group. Additional contrasts observing individual ROI activity between groups are discussed below.

### ***Group Differences in Individual ROIs***

Group comparisons of individual ROI activity between RD and TD groups were completed using independent samples t-tests by stimulus type. Data were bootstrapped to 1000 samples with bias corrected accelerated confidence intervals, and FDR corrected to account for multiple comparisons. Results from the unrelated word condition indicated four regions of interest where the RD group had significantly higher mean activation compared to the TD group, in the right and left SMA, the right rPFC, and the right IFG (table 2). Equal variance was assumed in all regions. Once again, these differences appeared to be driven by regions in which the RD group showed significant activity while the TD group did not. The TD group generally

presented a pattern of under-activity in the unrelated word condition – though this effect was never strong enough to reach significance when analyzed with FDR correction.

Further analysis in the false font condition revealed seven regions of interest with significant differences in activity between groups: in the left hemisphere, the SPLa and SPLb; and in the right hemisphere, the IPSa, IPSb, dPMC, SPL, and CrusI of the cerebellum (table 2). In each one of these regions, the RD group demonstrated higher mean activation during the false font condition in comparison to the TD group. Equal variances could not be assumed in the right SPL as the RD group had a variance more than four times greater than the TD group. However, given that the greater variance was equally distributed in the RD group which had three times as many participants, standard adjustments for variance were deemed to be acceptable. Equal variance was assumed for all other ROIs that reached significance.

Given the differences in WASI-II scores that were found between groups on the matrix reasoning subtest, a sensitivity ANOVA was conducted to determine whether group differences in ROI activity were driven by pre-existing differences in non-verbal IQ. Analysis revealed that group differences in ROI activity were maintained in the presence of non-verbal IQ in all significant ROIs in the unrelated word condition, and in the left SPLb, right SPL and right crusI in the false font condition. Group effects during the false font condition did not remain in the right dPMC, left SPLa, and both right IPSa and right IPSb when controlling for non-verbal IQ, however this did not appear to be due to a moderation effect. No interaction effects were found between non-verbal IQ and group status in relation to any significantly active ROI across all stimulus types. The analysis indicates the relationship between non-verbal IQ and observed ROI activity was constant across the range of IQs in unrelated word and pseudoword conditions, and

that non-verbal IQ had an inconsistent impact on observed ROI activity in the false font condition that was independent of group status.

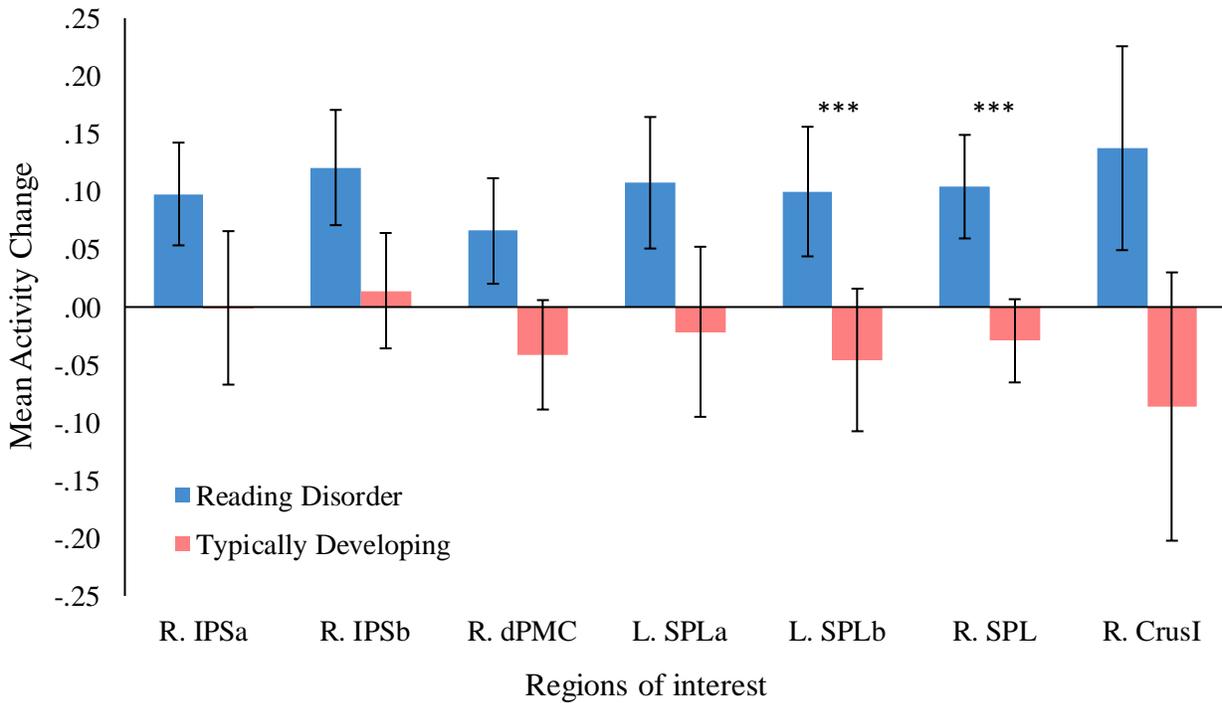
**Table 2.**

*Mean Activation Differences Between Groups*

Region	RD		TD		<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
False Font						
L. superior parietal lobule <sup>b</sup>	.10	.24	-.05	.14	2.66	<.001
R. superior parietal lobule*	.10	.20	-.03	.08	4.65	<.001
R. intraparietal sulcus <sup>b</sup>	.12	.22	.01	.11	2.20	.009
R. cerebellum crusI	.14	.40	-.09	.28	2.48	.005
R. dorsal premotor cortex	.07	.20	-.04	.11	2.39	.008
L. superior parietal lobule <sup>a</sup>	.11	.25	-.02	.17	2.26	.014
R. intraparietal sulcus <sup>a</sup>	.10	.20	.00	.15	2.18	.018
Unrelated Word						
R. supplementary motor area	.12	.24	-.03	.17	2.77	<.001
R. rostral prefrontal cortex	.09	.28	-.10	.18	3.17	<.001
L. supplementary motor area	.14	.28	-.03	.19	2.67	.002
R. inferior frontal gyrus	.13	.24	.00	.16	2.31	.010

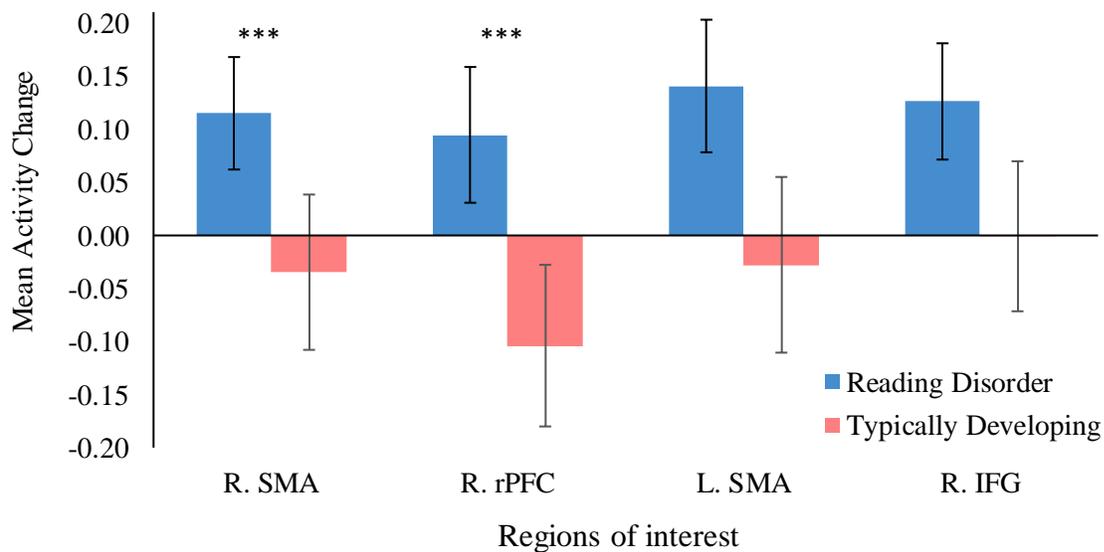
Data identified as significant after FDR correction. Degrees of freedom = 97

\*equal variances could not be assumed for this region (Degrees of freedom = 81.36)

**Figure 2:***Group Comparison of Activity in False Font Condition*

Comparison of mean activity change between reading disorder group and typically developing group in false font trials. Significant regions include right intraparietal sulcus (peak <sup>a</sup> and <sup>b</sup>), right dorsal premotor cortex, left superior parietal lobule (peak <sup>a</sup> and <sup>b</sup>), right superior parietal lobule, and right cerebellum crusI.

\*\*\* $p \leq .001$ , All other regions significant to  $p \leq .01$

**Figure 3:***Group Comparisons of Activity in Unrelated Word Condition*

Comparison of mean activity change between reading disorder group and typically developing group in unrelated word trials. Significant regions include right and left supplementary motor area, right rostral prefrontal cortex, and right inferior frontal gyrus.

\*\*\* $p \leq .001$ , All other regions significant to  $p \leq .01$

### Identifying Areas of Significant Activation

Although main effect analysis is an indicator of the significant differences present in ROI activity between groups, it does not identify whether ROIs in either group showed a significant change in *activation* during the FastLoc task (standard trials vs. 1-back trials) that was recognizably different from the background noise inherent to fMRI. Significant activation was determined by one-sample t-tests across TD and RD groups individually with a test value of 0 (C.I. 95%). Data were bootstrapped to 1000 samples with bias corrected accelerated adjusted confidence intervals. To correct for multiple comparisons a False Discovery Rate (FDR) correction was made for each stimulus condition (false font, pseudowords, and unrelated words) to best represent group differences in response to each stimulus type.

Starting with the false font condition, twelve ROIs showed significant activation in the RD group, and only one was suggested to be active in the TD group, however it did not remain after FDR correction. Similar results were found in the unrelated words condition where once again twelve ROIs had significant activation in the RD group, and no ROIs in the TD group remained significantly active after correction. Concurrent activation between groups was primarily found with the pseudoword condition, with eight ROIs showing significant activation in the RD group and five ROIs active in the TD group after correction. Out of the total seventeen ROIs, five in the false font condition (left IFG, bilateral MFG, and bilateral rPFC), six in the pseudoword condition (bilateral rPFC, bilateral MFG, right SPL and left SPLb), and five in the unrelated word condition (left SPLb, right SPL, bilateral dPMC, and right cerebellum) were determined to show no significant change in activation in both groups. (See supplementary table 1 and 2 for complete ROI activation data across stimuli.)

Activation analysis by FDR corrected t-tests echoed main effect analysis in a number of ways. The RD group had a greater number of significantly activated ROIs, particularly within false font and unrelated word conditions, while TD group did not have any ROIs showing significant activation in these word conditions. This effect compliments the group differences and interaction effects found in the false font and unrelated word conditions respectively and may suggest RD participants recruit the WM network to a greater degree than TD participants in while responding to the 1-back trials.

The pseudoword condition is unique in that there were no main differences found between RD and TD groups during analysis of main effects, however this stimulus condition was the only one in which the TD group showed a significant change in ROI activation that survived

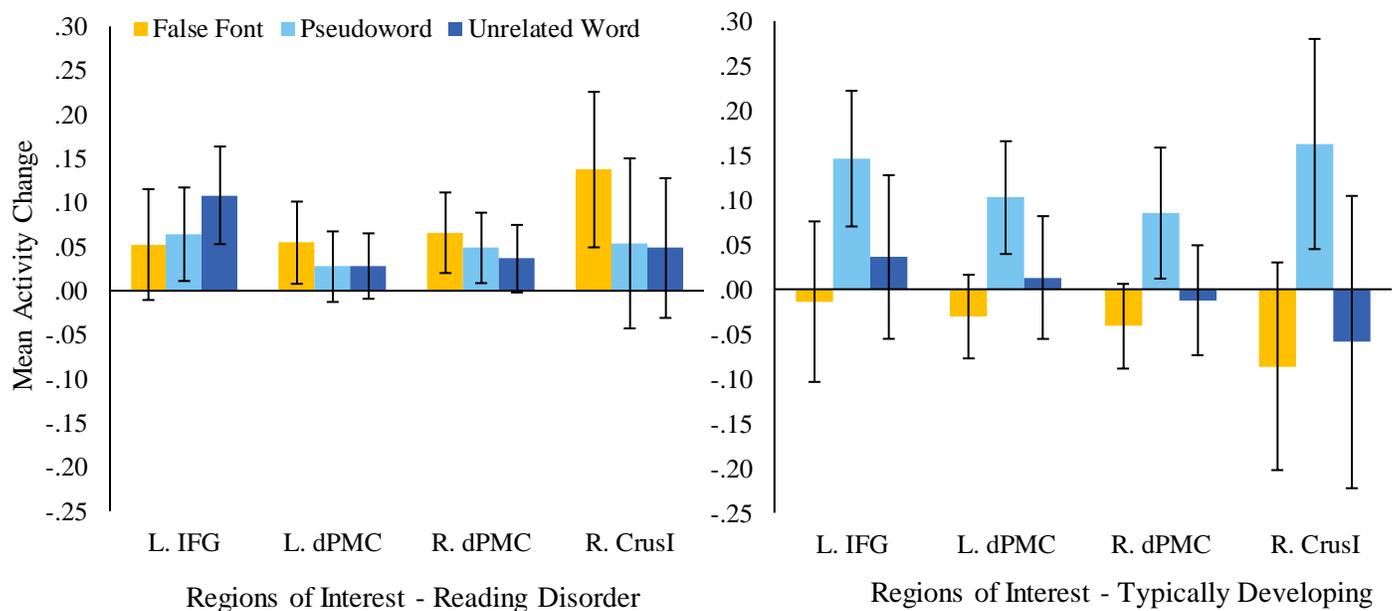
correction. Significant change in activation in the TD group was found in the left IFG, IPS, dPMC, SPLa, and right crusI of the cerebellum. The active ROIs in the TD group were largely left lateralized, with the left IFG and right crusI being specifically associated as sensitive to verbal stimuli. In the pseudoword condition, the RD group shared activity only in the left IFG and left IPS with the TD group. The remainder of the active regions in this condition were right lateralized (IFG, IPSa and IPSb, dPMC) with the exception of the SMA which saw bilateral activation unique to the RD group.

### **Network Activation Across Stimulus Types**

Repeated measure ANOVA comparisons on individual ROIs helped to evaluate activity differences across the three stimulus conditions. In the RD group, activity was largely indiscriminate between word types, with only the right SPL showing significant differences between stimulus conditions [ $F(2,152) = 4.464, p = .013$ ]. Pairwise comparisons revealed the main difference was in the false font condition which had significantly higher activation from the pseudoword condition ( $p = .028$ ) and unrelated word condition ( $p = .039$ ), Bonferroni corrected. This was the only region in which significant differences between stimulus types were calculated.

ANOVA comparisons revealed the TD group had five ROIs with significant main effects between stimulus types, the left IFG [ $F(2,42) = 3.300, p = .047$ ], left dPMC [ $F(2,42) = 5.192, p = .010$ ] and right dPMC [ $F(2,42) = 4.418, p = .018$ ], right crusI of the cerebellum [ $F(2,42) = 4.638, p = .015$ ], and the right rPFC [ $F(2,42) = 4.016, p = .025$ ]. The primary difference between word conditions diverged from what was seen in the RD group with the pseudoword condition showing significantly higher activation compared to the false font condition after Bonferroni

correction in the left IFG ( $p = .025$ ), left dPMC ( $p = .006$ ), right dPMC ( $p = .004$ ), and right crusI of the cerebellum ( $p = .016$ ; figure 3). Although these effects may suggest the expected verbal specificity in the left IFG and right crusI of the cerebellum, the presence of the same effect in the bilateral dPMC which were chosen as visual specific ROIs renders the results more difficult to interpret. The right rPFC had a unique pattern with pairwise comparisons showing a corrected main difference between the false font and unrelated word conditions ( $p = .040$ ) but no significant differences between the false font and pseudoword conditions. Finally, although there were no main effects in the left SPLa [ $F(2,42) = 3.145$   $p = .053$ ] and SPLb [ $F(1.486, 31.197) = 2.729$ ,  $p = .094$ ] that reached significance, both showed pairwise effects between the false font and pseudoword condition, with significantly higher pseudoword activation after correction (LSPLa  $p = .012$ , LSPLb  $p = .006$ ). The TD group had no significant activation or main effects in the right SPL for any one stimulus type.

**Figure 4:***Group Activation Across Stimulus Types*

Comparison of mean activity in regions of interest found to have pseudoword specificity in the typically developing group. Pairwise comparisons reveal significant main differences between false font and pseudoword conditions in the left inferior frontal gyrus ( $p = .025$ ), left dorsal premotor cortex ( $p = .006$ ), right dorsal premotor cortex ( $p = .004$ ), and right cerebellum crusI ( $p = .016$ ). No specificity was suggested in these regions in the reading disorder group.

**Exploratory Analysis of Behavioural Correlates***Main Effects*

Performance on the FastLoc task, identified by correct button press, revealed group differences in accuracy across all three stimulus types. ANOVA revealed a significant main effect of study group on performance accuracy was found across all stimulus conditions [ $F(1,147) = 20.544$   $p < .001$ ]. TD participants had high accuracy in both verbal conditions (pseudoword:  $M = .98$   $SD = .03$ , unrelated word:  $M = .99$   $SD = .03$ ) in comparison to RD participants (pseudoword:  $M = .87$   $SD = .13$ , unrelated word:  $M = .87$   $SD = .12$ ) which was statistically significant (pseudoword:  $t(95.90) = -6.92$ ,  $p < .001$ , unrelated word:  $t(95.94) = -7.21$ ,  $p < .001$ ). Accuracy was slightly lower for both groups in the false font condition (TD:  $M$

= .97  $SD = .05$ , RD:  $M = .86$   $SD = .15$ ) but was still significantly higher in the TD compared to the RD group [ $t(95.60) = -5.60$ ,  $p < .001$ ]. In both groups, errors were significantly more likely to occur due to misses in 1-back trials rather than false alarms on standard trials.

Between group comparison of CVLT-C measures identified significant group differences in long delay cued recall [ $t(50.89) = -2.367$ ,  $p = .011$ ], false positives [ $t(84.125) = 3.363$ ,  $p = .001$ ], and total intrusions [ $t(71.427) = 3.983$ ,  $p < .001$ ]. Neither measures of recall consistency or correct recognition hits had significant differences between RD and TD scores. All CVLT-C measures were strongly correlated with measures of performance accuracy.

### *Correlational Analysis*

Correlational analysis of ROI activity with behavioural measures was conducted across all 99 participants at once to best capture the normal range of all measures. Correlations of ROI activity onto measures of performance accuracy and CVLT-C scores revealed little convergence between the two behavioural measures when predicting for functional activity. Performance accuracy was negatively correlated with activity in the right dPMC ( $r = -.234$ ,  $p = .020$ ) in the false font condition, the right IFG ( $r = -.321$ ,  $p = .001$ ) in the pseudoword condition, and the bilateral SMA (left SMA  $r = -.333$ ,  $p < .001$ ; right SMA  $r = -.339$ ,  $p < .001$ ) and right rPFC ( $r = -.335$ ,  $p < .001$ ) in the unrelated word condition. All correlations remained significant following additional median split testing to account for the near perfect performance accuracy across the study.

Concerning CVLT-C measures across all participants: recall consistency was negatively correlated to the left SPL, both peaks of the right IPS, and right crusI of the cerebellum in the pseudoword condition. In contrast, long delay cued recall and correct recognition hits were

positively correlated to pseudoword activity the left MFG and right rPFC (table 3.) No significant correlations were found between the inaccurate recall measures and pseudoword ROI activity. The false font and unrelated word conditions did not have ROI activity that correlated with any CVLT-C measures associated with the three-factor model. (Summary of all main ROI-CVLT-C correlations can be found in supplementary table 3.) Secondary analysis on additional CVLT-C measures revealed negative correlations between the measure for List B free recall and activity in the bilateral SMA and right rPFC in the unrelated word condition, as well as negative correlations between immediate recall measures for List A Trial 1 and activity in the bilateral SPL, and right IPSb in the false font condition (table 4). Interestingly, unrelated word right rPFC activity also correlated with the measure for immediate recall List A.

**Table 3:**

*Correlations between Factor Related CVLT-C Measures and Pseudoword Activity*

	R. IPSa	R. IPSb	L. SPLb	R. CrusI	L. MFG	R. rPFC
Long Delay Cued Recall	-.100	.075	.175	.022	.213*	.242*
Correct Recognition Hits	-.035	.034	-.011	.089	.269**	.285**
Recall consistency	-0.278**	-.352**	-.221*	-.290**	-.169	-.050

\*Correlation significant at .05 level (2-tailed)

\*\*Correlation significant at .01 level (2-tailed)

**Table 4:**

*Correlations between Secondary CVLT-C Measures and ROI Activity*

	<u>Unrelated Word</u>			<u>False Font</u>		
	L. SMA	R. SMA	R. rPFC	R. IPSb	L. SPLa	R. SPL
List B free recall	-.265**	-.283**	-.281**	-.183	-.175	-.245*
List A Trial 1 recall	-.188	-.134	-.265**	-.252*	-.247*	-.241*

\*Correlation significant at .05 level (2-tailed)

\*\*Correlation significant at .01 level (2-tailed)

## Discussion

The primary goal of this study was to investigate activity in the WM network during single word decoding in young readers with or without reading disorder. By observing the change in functional activity between standard trials and 1-back trials across unrelated words, pseudowords, and false font conditions this study aimed to answer four questions addressing: 1) the fit of the FastLoc-R/A task in measuring activity in the WM network relative to single word decoding, 2) differences in WM activity between typically developing children and children with RD across unrelated word, pseudoword, and false font conditions, 3) specificity of the WM network to verbal and non-verbal stimuli, and 4) possible cognitive correlates between functional activity and verbal WM. It was discovered that the FastLoc-R/A task does measure the recruitment of the WM network relative to single word decoding. This activity was largely disparate between RD and TD participants, with the TD group showing expected WM specificity to pseudowords over all other word conditions, while the RD group showed WM network activity in six ROIs across all stimulus conditions. Pseudoword activity was moderately correlated to cognitive measures of verbal WM through the CVLT-C but did not correlate with performance accuracy.

### **Activity in the Working Memory Network Between Groups**

The design of this study focused on the FastLoc-R/A paradigm's utility in assessing reading and attention simultaneously. By pairing a passive reading task, with a 1-back task that requires active assessment of words in order to respond, the FastLoc-R/A task does not just measure general attention but attention that is specific to the reading process. In order to verify the last item in a trial to the one that came before it, that information must be held in storage

through phonetic, semantic, or visual cues. Previous studies using the FastLoc paradigm have demonstrated the utility of the task in identifying functional differences in attentional control and reading regions simultaneously (Arrington et al., 2019). The current study further extends this demonstration to the WM network. Less effortful cognitive processing can result in lower functional activity that does not negatively effect task performance (Barquero et al., 2014). Based on models of reading acquisition and WM capacity, it was expected that WM activity in the FastLoc-R/A task would be heightened for 1-back trials in RD participants compared to TD participants, due to RD participants' reliance on more effortful decoding strategies. Pseudoword and false font trials were also expected to elicit a greater recruitment of the WM network compared to the unrelated word trials, however this effect was not fully reflected in the findings of either group.

Within the TD group, higher activity in 1-back trials compared to the standard trials was only significantly identified within the pseudoword condition. The active ROIs during pseudoword trials were predominantly focused on reading associated regions (the left IFG and right crusI of the cerebellum) as well as left parietal regions and the left dPMC, which suggests left lateralization in conjunction with existing research on the verbal WM network in children (Barquero et al., 2014; D'Mello & Gabrieli, 2018; Thomason et al., 2009). The false font and unrelated words conditions, by comparison, were not associated with any significant increases in activity in the TD group and even showed patterns of decreased activity in 1-back compared to standard trials – though this never reached significance. Conversely, results from the RD group indicate a predominant increase in activity in 1-back compared to standard trials which was largely indiscriminate across unrelated words, pseudowords, and false font conditions. Six ROIs increased activity significantly across all stimulus conditions; the right IFG, bilateral SMA, and

bilateral IPS (including both right peaks). Additionally, the left IFG was significantly active during unrelated word and pseudoword trials, and the bilateral MFG and rPFC were active only for the unrelated word condition. Group differences in activity largely followed the expected models, as higher ROI activity was found in the RD group in false font and unrelated word, but not pseudoword trials, and lower performance accuracy was found in all trials. Common activity between RD and TD groups was found only within the left IFG and IPS during the pseudoword condition.

The dorsal-ventral model of reading suggests typically developing readers mainly utilize the ventral circuit for frequently encountered words but fall back on dorsal and anterior regions when encountering low frequency words or pseudowords that must be phonologically decoded (Pugh et al., 2001) Increased frontal and parietal activity in pseudoword but not unrelated word trials indicate TD participants may need to recruit the WM network more heavily in response to the 1-back task when using dorsal regions to read. Decoding through the dorsal circuit is a process which is less efficient due to the attentional resources it requires (Pugh et al., 2001). A significant increase in WM activity in pseudoword trials may suggest attentional resource management occurs at some level in single word reading to support phonological processing. However, this activity did not appear to negatively affect performance accuracy despite the negative correlation found between executive functioning and pseudoword activity in two of the five active ROIs in the TD group. Thus, the FastLoc-R/A task appears to measure activity specific to the WM network during single word reading in typically developing children, but only during pseudoword reading where additional attentional support may be necessitated.

As expected, the RD group showed a dramatically different pattern of activation reflecting increased difficulties with word identification and development of the ventral circuit. Compensatory dependence on the IFG during phonological decoding has been found in previous research on individuals with RD (Hoeft et al., 2011; Pugh et al., 2001), while posterior right hemisphere compensation has been found during both word and non-word reading tasks (Barquero et al., 2014). Increase in 1-back activation during word and pseudoword processing suggests RD participants may split attentional resources between word reading and responding to the 1-back task regardless of the familiarity of the words encountered. Importantly, this functional activity did not appear to improve performance accuracy, as children with RD had performance accuracy scores that were significantly below that of TD children across all trials. This is consistent with both the dorsal-ventral and attentional resource emancipation models of reading, indicating that increased reliance on the WM network may be the result of insufficient development of early reading skills (Fletcher et al., 2011; Richards & Berninger, 2008; Richlan et al., 2011). That significant activation was found in twelve ROIs in the false font condition – six of which were shared with the unrelated word and pseudoword conditions – suggests the FastLoc-R/A task identifies activation of the WM network that is not dependent on phonological or semantic processing in children with reading disorder.

### **Lateralization and Compensation**

As hypothesized, there was a distinct difference in activation across stimulus types between RD and TD participants. Among these expected differences, verbal-specific left hemisphere activity occurred only in TD participants, while RD participants had activity in both hemispheres across all conditions indicating reduced language specific lateralization. Increased right hemisphere activity in those with RD is well documented in the literature; right IFG and

prefrontal cortex activity in particular are known to compensate for reading difficulty in children and adults with RD who have responded positively to reading intervention (Barquero et al., 2014). However increased right IFG connectivity has also been seen as a positive predictor of reading ability in pre-reading children who are not at risk of RD (Benischek et al., 2020). Recently, research has suggested lateralization of language processing occurs as a function of early brain development, with typically developing readers expressing stable left lateralization around the age of 5 while children with RD do not (Weiss-Croft & Baldeweg, 2015).

In the current study, RD activity was significant across the right IFG, bilateral SMA, and bilateral IPS in all stimulus conditions and negatively correlated with cognitive measures of verbal WM. None of these regions were significantly active for any stimulus condition within the TD group, although right IFG activity was suggested in the false font condition. This disparity in activity patterns indicates RD participants may have relied on different strategies to complete the FastLoc task compared to their typically developing peers. Research on typically developing pre-reading age children have found connectivity between the right IFG and bilateral pre-motor areas to positively correlate with rapid naming measures of shapes and colours, while connectivity between the right angular gyrus and pre-motor regions positively correlated with early phonological processing tasks (Benischek et al., 2020). Right IFG activity corresponds with salience to attentional cues, as well as attentional shifting but does not appear to be selectively sensitive to verbal, object, or spatial cues (Hampshire et al., 2010; Nee et al., 2013). Likewise, bilateral SMA and IPS activity has been associated with updating and inhibition functions in response to verbal and spatial cues (Nee et al., 2013; Osada et al., 2019).

Stimulus indiscriminate activation across these three regions indicates RD participants may have been utilizing a language independent strategy for each stimulus type, resulting in less accurate task performance despite higher network activity, and that this strategy appears to utilize similar circuits to those that younger pre-reading children use during verbal tasks. This is not to suggest that RD children have WM network activation that is identical to younger controls. Research on pre-reading children at risk of RD have identified a number of structural and functional differences that are present before reading instruction (Vandermosten et al., 2016). However, observation of pre-reading activity may aid in the interpretation of similar activity in children with RD. Of particular interest in this study are the bilateral SMA and right IPS, each of which saw significant group differences in activity and are not often discussed within the reading literature – especially within adult and adolescent populations.

### **Identifying Verbal and Non-verbal Specificity**

Evidence of specificity in the WM network between verbal and non-verbal stimuli was largely inconclusive and reflected group determined specificity to verbal stimuli more so than region determined specificity.

Looking first at verbal trials, the left IFG was the only region consistently inactive for the false font condition and active for the pseudoword condition across both groups. However significant pairwise differences between the two stimuli were only found within the TD group, perhaps as a consequence of the apparent sensitivity of the RD group to the FastLoc task. Pairwise differences in TD ROIs were consistently found in all regions active for the pseudoword condition. Although pseudoword activity in the left IFG and right crusI may suggest verbal specificity, the same patterns were found in the right and left dPMC – regions previously

identified as sensitive to visual WM. Furthermore, the TD group saw significant activity of the left dPMC only in pseudoword trials. This is at odds with both the false font specific activity of the left dPMC in the RD group as well as Rottschy et al.'s meta-analysis indicating the dPMC to activate *only* during visual over verbal WM tasks (2012). Likewise, despite previous evidence associating the articulatory loop with right crusI activation, this region was only active in the RD group during the false font condition. For ROIs associated with visual specific WM, findings were even less consistent across groups. The left SMA demonstrated indiscriminate significant activity across all word types in the RD group and indiscriminate *non*-significant activity in the TD group.

Although this study chose the left SMA and bilateral dPMC as regions sensitive to visuospatial over verbal WM based on meta-analytic findings from previous literature (Owen et al., 2005; Rottschy et al., 2012), there is some evidence these regions may also play a role in the phonological memory as well. Alternative meta-analyses have also identified the left SMA to play a role in verbal maintenance alongside the left parietal cortex and right cerebellum (Attout et al., 2019), with Emch et al., (2019) going so far as to name the left SMA and left IFG as part of the articulatory loop. Individual studies have also found the premotor cortex to be involved in verbal short term memory (Majerus et al., 2006), though several still cite it as primarily associated with visuospatial maintenance. Another theory based on meta-analysis suggests that the SMA in conjunction with the superior frontal sulcus and bilateral IPS may play a part in the updating role of WM, which shifts attentional allocation based on priority (Nee et al., 2013). If this is the case, the indiscriminate activation of the bilateral IPS and SMA in RD participants may be explained by the updating function managed by the central executive rather than information storage in either the phonological loop or visuospatial sketchpad. Lastly, the SMA is

also well known for its role in the planning of movement, particularly during situations where incorrect responses must be inhibited to execute the correct movement – such as is the case in the FastLoc where a button must be pressed for 1-back trials only (Nachev et al., 2007). Given that RD participants had lower performance accuracy compared to typically developing controls, motor planning may also account for the difference in SMA activity between the two groups but speaks less towards the selective dPMC activity found. Similarly, while the cerebellum has frequently been suggested to play a part in the articulatory loop, it has also been implicated in temporal processing and prediction (Sokolov et al., 2017). These functions while certainly a part of reading and language processing, are arguably not specific to the articulatory loop or phonological memory.

The lack of consistency in visual specific ROIs may also be due to the nature of the FastLoc test which utilizes temporal memory instead of spatial. The visuospatial sketchpad has been evidenced as suited to storing and manipulating complex information within a spatial snapshot, but it is not suited to maintaining the temporal order of information (Baddeley, 2000). A temporally based memory task, such as the 1-back trials in this study may be unlikely to access the visuospatial sketchpad at all, even in case of non-verbal stimuli with no phonological representation. Based on this evidence a more suitable approach may have been to identify ROIs associated with the sequential order of visual information rather than visuospatial memory as a whole. The phonological loop is primarily known as a memory store based on phonological and semantic information that is suited to temporal tasks (Rudner & Rönnerberg, 2008). However recent neuroimaging studies have characterized that regions specific to temporal order outside of semantic and phonological information do begin to differentiate in children aged 7-12 (Attout et al., 2019). While it was initially predicted that the false font condition would elicit significant

activity in visuospatial specific regions of the WM network, this is unlikely to be true in the case of the FastLoc paradigm. Activation of visuospatially sensitive ROIs in a verbal condition may simply be a result of the nature of the task presented, as well as a testament to how multimodal many regions known for executive functioning can be.

### **Does Network Activity Mean Working Memory Activity?**

In any study, interpreting the effects of functional activity on behaviour can be a difficult road to navigate. Inclusion of behavioural correlates does not always make this interpretation easier as neuroimaging methods may identify activity that underlies behavioural metrics but does not correlate with it, or activity that is irrelevant to those behavioural metrics but does correlate with it. Thus, in any imaging study caution must be taken when interpreting behavioural effects. Evidence from the current study found that ROI activity in the FastLoc task was most commonly negatively correlated to both CVLT-C and performance accuracy measures. It may at first seem counterintuitive for activity in regions previously identified as part of the WM network to share a negative correlation with cognitive measures of WM, however it is important to interpret this relationship within the full context of its variables.

In this study ROI activity refers to the change in BOLD activity between standard and 1-back trials – just a fraction of the overall activity that occurred within the WM network across trials. As such negative correlations between CVLT-C measures and ROI activity does not suggest these regions are negatively associated with verbal WM. Rather, a negative correlation may suggest that a higher level of activity in these regions did not result in an increase in WM performance, perhaps due to the increased cognitive load when the 1-back task was introduced. There are a few possible interpretations of this effect.

Behavioural correlations in the pseudoword condition were some of the strongest, due to the fact that they corresponded with CVLT-C measures that were significantly associated with factors of executive functioning and verbal memory, and because this stimulus condition was the only one that saw significant activation patterns in both groups. Negative correlations were found between percent recall consistency, which corresponds with executive functioning, and activity in the right IPS, left SPL, and right cerebellum. Given there were no group differences in activity found in the pseudoword condition and both the left SPL and right cerebellum were significantly active in the TD group, it is less likely this effect is due to activity that is unique to the RD group. This is tentatively positive, as it suggests the FastLoc task identified activity in the WM network which was not unique to group status but was linked to memory performance and maintenance.

Increased activity within the WM network at the cost of executive performance may be a reflection of a central executive that is unable to meet the demands of a task while maintaining the memory systems. Active rehearsal and retrieval of information has been evidenced to recruit attentional control heavily and can negatively impact task performance as cognitive load increases (Lavie, 2010; Morey & Cowan, 2005). Unfortunately, none of these regions went on to correlate with performance accuracy on the FastLoc task leaving no direct indication that increased activity in these regions had any impact on task performance even though significant differences in task accuracy were present between groups in the pseudoword condition. Interestingly, functional imaging research has found that activation of the WM network may have a very different relationship with cognitive demand in children compared to adults (Thomason et al., 2009). While children were found to have cognitive load related increases in frontal and parietal activity in response to a verbal WM task, they were unable to recruit these

regions with the same intensity as adults to supplement task performance (Thomason et al., 2009). As a result, small increases in functional activity may represent very large decreases in task performance in child populations. If this is the case, it is possible ROI effects on task performance were not identified in this study due to the high variability in BOLD measures leading to decreased sensitivity to detect changes. Furthermore, while the measure of percent recall consistency is fairly parallel to measures of performance accuracy on the FastLoc task – both measure immediate short-term recall – the CVLT-C task uses a list of fifteen words placing a much higher demand on cognitive load than the FastLoc’s four word tetrads. The skewed performance accuracy measures of the FastLoc were evident of a task that may not have been difficult enough to appropriately measure cognitive load effects in all but the poorest readers.

At this junction, it cannot be concluded whether or not the activity in the WM network identified in the FastLoc task is related to behavioural measures of WM. However, there are a few findings which may speak positively towards this possibility and require further study. Future research looking to more clearly characterize ROI effects on verbal WM performance in young readers may require another analysis approach that simplifies study design to increase statistical sensitivity or uses a more direct measure of WM activity than the subtraction analysis used in this study. Increasing the difficulty of the n-back task in the FastLoc may also help to reduce ceiling effects on performance accuracy.

### *Specific Group Differences in Unrelated Word Trials*

Behavioural correlates of interest were also found within ROIs that saw group differences. In unrelated word trials, the right IFG, bilateral SMA, and right rPFC were all found to have significantly greater mean activity change in the RD group compared to the TD group.

Of these four regions, all but the right IFG were negatively correlated with performance accuracy on the FastLoc task. Negative correlations were also found between mean activity change and CVLT-C measures of list B free recall, suggesting the group differences found in ROI activity converge with behavioural measures of verbal recall. Several neuroimaging studies have identified activity in the dorsolateral PFC that appears to play a compensatory role in reading for children with RD (Aboud et al., 2018), while premotor activity corresponds with verbal maintenance and articulatory recoding in young readers (Attout et al., 2019; Hung et al., 2019). However, this study found activation in these regions did not improve FastLoc performance in comparison to the typically developing group, echoing the more effortful compensatory activity of the anterior circuit explained in the dorsal-ventral model of reading. Previous research regarding the anterior circuit in reading development has focused primarily on the clear role of the IFG (Pugh et al., 2001). It has only been in more recent years that interaction effects from regions considered extraneous to the reading network have become more thoroughly scrutinized for their role in reading development (Aboud et al., 2018; Church et al., 2019). This study suggests the bilateral SMA and right rPFC may be viable candidate regions to further assess activity in the WM network that is specific to children with RD during verbal recall or word ID.

### ***Specific Group Differences in False Font Trials***

Comparison ROI activity in the false font condition is more difficult to interpret despite the negative correlations found between the left IPS and bilateral SPL with the CVLT-C scores of List A immediate free recall. Non-verbal IQ was found to be a significant covariate which predicted mean ROI activity in false font trials above the rate that group status did in several regions, however Non-verbal IQ did not appear to *interact* with group status itself. These results indicate activity in the right IPS, right dPMC, and left SPLa in the false font condition may be

primarily due to group differences in non-verbal IQ rather than group status, while activity in the left SPLb, right SPL, and right crusI may be still be associated with group status. Although it may be disappointing to find that unanticipated group differences in non-verbal IQ, and not the intended group differences in reading ability, accounted for much of the significant ROI activity in false font trials, it is less surprising that non-verbal IQ would have a strong influence over the similarly non-verbal false font condition. Despite the fact that this study controlled for intellectual disabilities during recruitment, verbal and non-verbal IQ measures were still statistically lower in the RD group across all WASI measures – although IQ was not significantly lower than the standardized *average*, group differences were still present. This could have occurred for a variety of reasons, as the presence of reading disorder can adversely effect performance on IQ tests (Morris et al., 2012), RD is often comorbid with other learning and developmental disorders (D’Mello & Gabrieli, 2018), and pre-reading children at risk of dyslexia have shown mild deficits in both verbal and non-verbal IQ measures (van Bergen et al., 2014). It can perhaps be considered consistent with the literature that while non-verbal IQ had a large influence over false font ROI effects, this influence was negligent during both verbal conditions, indicating IQ had no major influence on single word reading in RD participants even when measured through functional activity.

The relationship between false font ROI activity and non-verbal IQ may be a representation of the executive deficits that have been theoretically stated but inconsistently identified in RD populations (Church et al., 2019; van der Sluis et al., 2004). This study found a consistent negative relationship between CVLT-C measures of immediate recall and false font ROI activity. However, while ROI activity in the RD group was associated with poorer immediate recall, it was not associated with poorer task performance, the List A immediate recall

measure was not a significant contributor to any cognitive correlate in the three factor model used, and the influence of confounding comorbid learning disorders was not specifically characterized. Ultimately, the nature of how non-verbal executive functions relate to reading acquisition and intervention response are still poorly understood and require more research and replication. No strong inferences can be made regarding the group differences in false font ROI activity at this point.

### **Possible Confounds and Limitations**

#### ***Motor Activation***

The current study utilized a task which included a button press as a part of its response and observed mean activity in ROIs that are known to be involved in the planning and execution of motor sequences. Given that a button press was only a required response in 1-back and not reading trials, there is potential that some of the mean activity identified by the FastLoc task represents change in activation due to the button press itself rather than purely task related activity. Many regions involved in executive functioning also play some role in motor function or the planning and coordination of movements (Hoshi & Tanji, 2007). The two regions of interest most likely to be confounded by motor activation related to the act of pressing a button itself, and not making a decision on whether or not to execute the motor sequence for a button press are the SMA and dPMC. Both the bilateral SMA and dPMC saw significant activity in this study, however this activity was not consistent between the two groups as might be expected if the effect was being driven primarily by a motor confound. Performance accuracy on the FastLoc task was above 85% in both groups across all stimulus types, indicating both groups were fairly consistent in correctly responding to trials that required a motor response.

It is worth noting that the motor response required in 1-back trials across all stimulus conditions was always a right hand button press. As such confounding motor activity would be most likely to occur in the left hemisphere across all three stimulus types. Bilateral SMA activity in the RD group and pseudoword specific left dPMC activity in the TD group is less consistent with an expected motor confound and may indicate ROI effects in these regions are not wholly representative of motor activity alone.

### ***Comorbid Conditions***

Some participants within the RD group of this study were also identified to have significant inattentive symptoms, reflective of ADHD, and/or a specific language impairment. These participants were included within the study as comorbid developmental and learning conditions are quite common within the RD population (D’Mello & Gabrieli, 2018; McGrath & Stoodley, 2019). The decision to include participants with comorbidities can make it more difficult to establish the direct relationship between ROI activity and the presence of RD. However, this study did not seek to establish any direct inferences between these two measures. The two primary goals of this study were to provide a proof of concept that the FastLoc task could be used to measure WM activity, and to identify descriptive differences in network activity between RD and TD groups. To suit the purposes of this study, the choice to include participants with comorbidities provides descriptive data that is more representative of what might be found in a typical RD population at this age range. As research in this area becomes more solidified, it may prove beneficial to further separate RD participants to account for comorbid conditions.

### *Limitations*

Functional imaging studies working to characterize the relationship between executive functioning and early reading skills are at this point still few and far between. Gaps in our current knowledge as well as challenges unique to fMRI methodology resulted in some limitations in the current study.

One of the larger limiting factors to the analysis of data in this study was the lack of control ROIs. While the activity found in the WM network appeared to reflect some aspects of verbal specificity and task performance, inclusion of control ROIs not expected to be active during the FastLoc task could have increased the power of these findings significantly. Since this study subtracted reading and n-back trials to isolate mean activity change related to WM, carefully chosen control ROIs would not be expected to activate as a result of unrelated activity. Candidate ROIs to act as controls would need to be carefully considered however, as executive functioning is difficult to classify to any one area of the brain and regions relating to both motor activity and the dorsal reading circuit would represent confounds. Choosing ROIs that represent the ventral network is one possible solution when looking across a range of readers but runs the risk of increasing the complexity of interpretation if comparing group effects.

With consideration to the neuroimaging task itself data on the false font condition was by far the most difficult to interpret meaningfully. Future research may consider inclusion of other non-verbal conditions similar to false font as unexpected but identifiable differences between groups were detected. With no other non-verbal stimuli present it is unclear if the differences found between groups would have been persistent to non-verbal stimuli or an artefact of the false font condition alone. In the FastLoc task, each of the eight total stimulus conditions had a

maximum of 24 trials per participant, but some participants may have had a few as 8 trials per stimulus type. For the false font condition, which saw the highest variability and lowest performance accuracy across measures more trials may be needed in order to accurately assess significant activation. Aside from simply including more runs per participant (which would increase in scanner time) future research using this task might substitute 2 of the verbal conditions for 2 non-verbal conditions. In this way all non-verbal and verbal conditions within the task could be assessed individually or consolidated to increase accuracy of detected activation.

### **Future Directions**

There are a number of directions research future could follow, some within the context of the longitudinal data used in this study. The current study observed functional and behavioural data from only the first timepoint of a six year longitudinal study on the efficacy of reading intervention. It did not observe functional changes between pre-intervention and post-intervention fMRI data or attempt to characterize any pre-intervention data based on intervention response. Instead, the current study established a proof of concept that the FastLoc task can be used to measure activity within the WM network, and that there appear to be some differences in WM network activity between children with and without RD. With this established, future research can focus on post-intervention data to identify whether or not reading intervention promotes changes in functional activity in the WM network, or retroactively if WM network activity predicts for intervention outcome.

There is still competing evidence as to whether successful reading intervention in children with RD promotes normalization of the reading network to a left lateralized system, or

compensation in which right hemisphere connections to the reading network become more robust (Aylward et al., 2003; Hoeft et al., 2011; Koyama et al., 2013; Richards & Berninger, 2008).

Evidence of functional changes in the WM network over the course of intervention – which also saw a strong pattern bilateral activity in RD participants – may help to contextualize changes in the reading network over time. The WM network is of particular interest as executive functioning underlies the development of any learned skill – accompanying changes to the WM network could help to establish a baseline to better understand how the reading network is likely to develop. Executive functioning is often used as a cognitive predictor for academic growth in other domains for this very reason, but due to the difficulties of measuring each skill in isolation the relationship between executive functioning and reading outcome has never been clearly defined (Church et al., 2019; Gerst et al., 2017). Future imaging research focusing on the link between WM and early reading skills is a necessary next step towards defining this relationship.

When considering the practical applications for reading research, predicting for and increasing positive intervention response is a primary concern. A small number of fMRI studies have identified that prefrontal activation and executive control networks may be effective mediators of intervention response (Aboud et al., 2018; Nugiel et al., 2019). While the evidence is currently tentative and requires replication across larger subject groups it is an encouraging lead for what could be a biological predictive variable to determine who is likely to benefit from reading intervention. Data from the FastLoc task makes a strong candidate for future research on this effect due to its previously established capability to measure reading and attentional control activity simultaneously (Arrington et al., 2019), as well as its now established ability in measuring WM activity. Reliable predictive variables for reading intervention outcome are currently few and far between, which brings significant repercussions to low responders who

often require a more intensive reading program than typical broad-scale interventions employ (Al Otaiba & Fuchs, 2006; McMaster et al., 2005). Establishing a reliable predictor for reading intervention outcome could greatly influence intervention efficacy as well as benefit development of personalized intervention plans.

## **Conclusion**

The relationship between WM and foundational reading skills exists within a strong theoretical basis, however research utilizing behavioural and cognitive metrics is often unable to appropriately define this relationship in a consistent manner. As a result, WM is often mainly considered in the context of reading comprehension. Neuroimaging methods are uniquely suited towards observation of this relationship across development, but few studies so far have sought to measure WM activity *during* the act of reading. In an effort to provide neuroimaging methods capable of measuring WM and simple word reading simultaneously, this study investigated the FastLoc – R/A task’s capability in measuring WM activity during a reading task in an elementary school age population with and without RD.

The study found that the FastLoc task did capture activity in the WM network that was specific to the 1-back task. The nature of this activity differed significantly between participants with and without reading disorder, such that typically developing participants saw strong left lateralized network activity only when responding to pseudoword trials while participants with reading disorder had a bilateral pattern of activity which was persistent when responding to both verbal and non-verbal trials. Results from the typically developing group reflect reading development theories suggesting WM activity should be highest when responding to words that must be phonologically decoded. Similarly, results from the group with reading disorder suggests

a pattern of overactivity that may be related to the poorer cognitive measures of verbal WM which are commonly found within this population. In both accounts, the findings of this study describe a significant contrast in WM network activity between children with and without reading disorder and underline the importance of untangling the relationship between WM and early reading skills.

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**Supplementary Table 1.***One Sample t-tests for Reading Disorder Group*

Region	False Font				Pseudoword				Unrelated Word			
	<i>M</i>	<i>t</i>	BCa 95% C.I.		<i>M</i>	<i>t</i>	BCa 95% C.I.		<i>M</i>	<i>t</i>	BCa 95% C.I.	
L. inferior frontal gyrus	.052	1.72	-.002	.107	.064	<b>2.40*</b>	.012	.124	.108	<b>4.01***</b>	.057	.162
R. inferior frontal gyrus	.115	<b>4.43***</b>	.061	.169	.095	<b>4.42***</b>	.054	.140	.126	<b>4.57***</b>	.071	.185
L. supp. motor area	.091	<b>3.05**</b>	.031	.156	.101	<b>3.22***</b>	.040	.155	.141	<b>4.46***</b>	.080	.212
R. supp. motor area	.080	<b>3.04**</b>	.028	.136	.088	<b>3.35**</b>	.037	.137	.115	<b>4.28***</b>	.063	.175
L. intraparietal sulcus	.118	<b>4.21***</b>	.065	.179	.080	<b>3.21**</b>	.032	.127	.086	<b>3.94***</b>	.041	.129
R. intraparietal sulcus <sup>a</sup>	.098	<b>4.38***</b>	.055	.144	.065	<b>2.93**</b>	.023	.108	.050	<b>2.28*</b>	.006	.097
R. intraparietal sulcus <sup>b</sup>	.121	<b>4.85***</b>	.074	.171	.084	<b>3.54***</b>	.034	.140	.066	<b>2.67*</b>	.014	.129
L. dorsal premotor cortex	.055	<b>2.35*</b>	.012	.101	.027	1.37	-.017	.069	.028	1.50	-.011	.069
R. dorsal premotor cortex	.066	<b>2.87*</b>	.020	.117	.049	<b>2.46*</b>	.012	.085	.036	1.87	-.005	.076
L. superior parietal lobule <sup>a</sup>	.108	<b>3.76**</b>	.054	.167	.050	2.00	.000	.105	.071	<b>3.11**</b>	.024	.116
L. superior parietal lobule <sup>b</sup>	.100	<b>3.59**</b>	.050	.151	.054	2.06	.005	.105	.014	0.50	-.049	.075
R. superior parietal lobule	.104	<b>4.68***</b>	.061	.144	.016	0.72	-.026	.057	.018	0.73	-.032	.068
R. cerebellum crusI	.137	<b>3.05**</b>	.049	.238	.054	1.11	-.035	.144	.049	1.23	-.033	.136
L. middle frontal gyrus	.043	1.46	-.024	.104	.041	1.64	-.007	.090	.097	<b>4.09**</b>	.050	.153
R. middle frontal gyrus	.061	2.21	.006	.118	.046	1.98	.002	.091	.072	<b>3.30**</b>	.026	.117
L. rostral prefrontal cortex	.043	1.96	-.001	.112	.010	0.44	-.039	.067	.079	<b>3.49***</b>	.033	.123
R. rostral prefrontal cortex	.056	1.46	-.016	.138	.026	0.91	-.023	.074	.095	<b>3.00**</b>	.024	.158

Data identified as significant after FDR correction. Degrees of freedom = 76 for each stimulus type.

\* $p \leq .05$ , \*\* $p \leq .01$ , \*\*\* $p \leq .001$

**Supplementary Table 2.***One Sample t-tests for Typically Developing Group*

Region	False Font				Pseudoword				Unrelated Word			
	<i>M</i>	<i>T</i>	BCa 95% CI		<i>M</i>	<i>t</i>	BCa 95% CI		<i>M</i>	<i>t</i>	BCa 95% CI	
L. inferior frontal gyrus	-.014	-0.31	-.091 .062		.146	<b>3.85**</b>	.072 .216		.036	0.80	-.054 .123	
R. inferior frontal gyrus	.071	2.45	.014 .122		.059	1.62	-.011 .126		-.001	-0.02	-.067 .068	
L. supp. motor area	.039	1.05	-.035 .102		.094	1.74	-.015 .214		-.028	-0.67	-.098 .041	
R. supp. motor area	.045	1.43	-.012 .098		.072	1.71	-.021 .170		-.035	-0.94	-.104 .033	
L. intraparietal sulcus	.055	1.83	.010 .094		.132	<b>4.71***</b>	.078 .189		.107	2.11	.002 .211	
R. intraparietal sulcus <sup>a</sup>	-.001	-0.02	-.052 .049		.049	1.61	-.007 .109		.042	1.42	-.019 .092	
R. intraparietal sulcus <sup>b</sup>	.014	0.58	-.028 .057		.073	2.29	.013 .132		.045	1.28	-.022 .106	
L. dorsal premotor cortex	-.031	-1.29	-.073 .009		.102	<b>3.30**</b>	.044 .157		.013	0.39	-.053 .079	
R. dorsal premotor cortex	-.041	-1.72	-.085 .001		.085	2.34	.018 .150		-.012	-0.41	-.066 .042	
L. superior parietal lobule <sup>a</sup>	-.021	-0.59	-.085 .042		.096	<b>3.02**</b>	.032 .159		.027	0.66	-.054 .099	
L. superior parietal lobule <sup>b</sup>	-.046	-1.49	-.101 .004		.080	2.40	.016 .147		-.008	-0.17	-.104 .073	
R. superior parietal lobule	-.029	-1.62	-.061 .004		.051	1.90	-.001 .107		.000	0.01	-.071 .068	
R. cerebellum crusI	-.086	-1.44	-.189 .008		.162	<b>2.79**</b>	.055 .275		-.059	-0.72	-.219 .092	
L. middle frontal gyrus	.020	0.56	-.052 .088		.096	2.41	.019 .172		-.001	-0.03	-.082 .077	
R. middle frontal gyrus	.012	0.57	-.027 .049		.067	2.05	-.002 .148		-.023	-0.56	-.109 .056	
L. rostral prefrontal cortex	-.009	-0.33	-.066 .043		.081	2.54	.017 .147		.005	0.14	-.069 .083	
R. rostral prefrontal cortex	.063	1.58	-.011 .130		.046	0.82	-.062 .188		-.104	-2.74	-.181 -.019	

Data identified as significant after FDR correction. Degrees of freedom = 21

\* $p \leq .05$ , \*\* $p \leq .01$ , \*\*\* $p \leq .001$

**Supplementary Table 3.***Median Correlations between all ROIs and CVLT-C Dimensions*

CVLT Dimensions	False Font		Pseudoword		Unrelated Words	
	Median	Significance	Median	Significance	Median	Significance
List A Trial 1 Free Recall Total Correct	-.177	.253	.083	.414	-.052	.610
List A Trial 5 Free Recall Total Correct	-.085	.403	.093	.364	-.121	.236
List B Free Recall Total Correct	-.123	.226	.039	.703	-.104	.307
List A Short Delay Free Recall Total Correct	.071	.485	-.054	.595	-.041	.687
List A Short Delay Cued Recall Total Correct	-.079	.440	-.075	.465	.064	.531
List A Long Delay Free Recall Total Correct	-.075	.466	.086	.397	.032	.757
List A Long Delay Cued Recall Total Correct	-.102	.230	.098	.335	.060	.556
Semantic Cluster Ratio	.123	.227	.051	.618	.038	.714
Percent Recall Consistency	-.066	.464	-.093	.361	-.053	.606
Correct Recognition Hits	.059	.575	.055	.601	-.074	.479
Intrusions (Free and Cued Recall)	.048	.637	-.053	.606	.112	.271
False Positives (Total)	-.052	.619	-.052	.624	.092	.380

*N* = 98