Exploring the Relationship between Working Memory Deficits and Reading Difficulties

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ABSTRACT

This study explored the relationship between working memory (WM) deficits and reading difficulties using secondary data analysis on data collected from 63 English speaking students in two urban school divisions in Saskatchewan participating in a larger SSHRC funded study (Marche, McIntyre, Claypool, 2013). First, this study addressed whether the WM profiles of individuals with reading difficulties were different from those of individuals without reading difficulties. The results showed that individuals with reading difficulties scored lower than individuals with average reading ability on measures of verbal short-term memory (STM), verbal WM, and visuospatial WM. Second, this study looked at the differential effects of computer-based WM training on the WM profiles of children with and without reading difficulties. The results showed that after WM training, there was a difference between the visuospatial STM scores of individuals with and without difficulties, when reading ability was determined by the combination of a decoding and comprehension task. Furthermore, a difference was also noted between the visuospatial WM scores of individuals with and without word decoding difficulties, and the visuospatial STM, verbal WM, and visuospatial WM scores of individuals with and without reading comprehension difficulties. Additionally, the verbal STM scores of individuals with reading comprehension difficulties were marginally different than the scores of individuals without. No differences were found between individuals who did not participate in WM training. The limitations of the study, as well as the implications for practice and future research, are discussed.

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DEDICATION

This thesis is dedicated to my family and to all those who have struggled with learning difficulties. May this contribute in some small way to understanding learning difficulties and determining effective ways to provide support.

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Chapter 1: Introduction

Reading is a crucial skill that many children have difficulty acquiring (Strickland, 2002). Eighty percent of the 4% of children diagnosed with a learning disability have difficulties in the areas of reading and related language functions (Milan, Hou, & Wong, 2006). There are many interventions available to individuals with reading difficulties (e.g., developing phonetic awareness skills, teaching students to use context to enhance word recognition and comprehension, teaching structural analysis skills; Smith, Polloway, Patton, Dowdy, & McIntyre, 2012). These interventions vary in effectiveness (Smith et al., 2012) possibly because of the underlying cause of the reading difficulty. One cognitive factor that is related to reading difficulties is working memory (WM; Dehn, 2008). Individuals with reading difficulties and WM deficits may require additional interventions other than traditional phonological training. Weak WM may make it difficult for individuals with reading difficulties to become proficient readers even with extensive phonological training. Therefore, it is important to further explore the relationship between WM and reading difficulties in order to determine if additional interventions would be beneficial.

WM is a system that is used for temporarily holding and manipulating information (Baddeley, 1992; 2010). A variety of models have been proposed to explain the role and functions of WM. Four key models include: the WM model proposed by Baddeley and Hitch (1974), the *executive attention model* proposed by Engle and colleagues (Engle, 2002; Kane, Conway, Bleckley, & Engle, 2001), the *embedded-process model* proposed by Cowan (2005), and the *integrated model* of WM proposed by Dehn (2008).

The integrated model of WM (Dehn, 2008) was used to guide the current study. This model pulls together information from a variety of sources in order to provide a model that is relevant to academic learning and offers a more complete understanding of the effects of WM deficiencies. In this model, Short-term Memory (STM), Long-term Memory (LTM), and WM are all seen as independent and distinguishable from one another. Several components are included in this model. Specifically, phonological/verbal STM is a component of memory that is passive and briefly stores speech based information. Verbal WM processes verbal information from short-term storage or retrieved verbal information from long-term storage. Visuospatial STM is a component of memory that is passive and briefly stores visual and spatial information. Visuospatial WM processes visual and spatial information from short-term or long-term storage.

Executive WM is the part of memory that is involved in the coordination and management of the various components of memory. LTM is an information storage system in which retrieval of information can occur automatically and passively (Dehn, 2008). "Working memory, which is often the interface between the two storage systems (i.e., STM and LTM), *works* both with units temporarily retained in STM and with activated permanent units from LTM" (Dehn, 2008, p. 50). Furthermore, STM can encode information into LTM and LTM can activate and retrieve information. To illustrate, when decoding an unfamiliar word, individuals must store the phonological sequence in STM, blend the phonemes into a word using WM, and also utilize prior knowledge from LTM, concurrently.

WM is related to overall academic achievement (De Jong, 1998; Engle, Tuholski, Laughlin, & Conway, 1999; Swanson & Berninger, 1996; Swanson, 2000). Low WM capacity can have an impact on general cognitive functioning, as well as acquisition of skills and knowledge (Dehn, 2008). Children with WM deficits: have difficulty with tasks requiring both the storage and retrieval of information, have difficulty keeping their place during assignments, and are poor at monitoring the quality of their work and often require extra help in the classroom (Alloway, Gathercole, Kirkwood, & Elliott, 2009). These children tend to get easily distracted and have difficulty remembering and following instructions. Individuals with low WM capacity are more likely to experience lack of focus when engaged in demanding cognitive activities (Kane et al., 2007). That is, these individuals may have difficulty organizing all of the information necessary for the mental activity because of an overloaded WM (Gathercole & Alloway, 2008). For example, academic achievement is impacted by low WM capacity (Dehn, 2008), and children with poor WM generally achieve low scores on measures of reading and math (Gathercole & Alloway, 2008).

Difficulty learning to read has been correlated with low WM capacity (De Jong, 1998). High demands on a limited resource pool make it difficult for children with low WM capacities to maintain information during reading (Swanson & Jerman, 2007). For example, when decoding an unfamiliar word, beginning readers must hold on to the sounds letters make long enough to sound out the entire word, which would be more difficult with low WM capacity (Dehn, 2008). Low WM capacity has an effect on the acquisition of foundational skills (e.g., word decoding), as well as on reading comprehension (Gathercole & Alloway, 2008). There is conflict in the literature regarding which components of WM are most likely involved in the reading process (De Jong, 1998; Pickering & Gathercole, 2004; Swanson & Jerman, 2007). For example, reading difficulties have been found to be related to: deficits in verbal WM (e.g., Cohen-Mimran & Sapir, 2007; Compton, Fuchs, Fuchs, Lambert, & Hamlett, 2012; Booth, Boyle, & Kelly, 2014; De Jong, 1998; Nevo & Breznitz, 2013; Swanson & Jerman, 2007), deficits in verbal STM (e.g., Cohen-Mimran & Sapir, 2007; Wang & Gathercole, 2013), no deficits in verbal STM (e.g., De Jong, 1998; Nevo & Breznitz, 2013; Swanson & Jerman, 2007), deficits in visuospatial STM and visuospatial WM (e.g., Pham & Hasson, 2014; Wang & Gathercole, 2013; Gathercole, Alloway, Willis, & Adams, 2006), or to no WM deficits (e.g., Bayliss, Jarrold, Baddeley, & Leigh, 2005; Pickering & Gathercole, 2004; Van der Sluis, Van der Leij, & De Jong, 2005). Some of these incongruities can be explained by the use of different measurement tools to assess WM and the different components of WM that are assessed (i.e., how they are defined and divided). The current study added to the literature by using the Automated Working Memory Assessment (Alloway, 2007), a standardized WM assessment tool that measures several components of WM. It is important to consider several components of WM in order to determine if reading difficulty is related to specific WM weaknesses.

Exploring the relationship between WM and learning difficulties can provide valuable information concerning effective evidence-based interventions (Dehn, 2008). A large amount of research is focused on improving WM through a variety of interventions. Two interventions that have been used to improve WM are strategy training (i.e., rehearsal, imagery, or semantic strategies (Holmes, Gathercole & Dunning, 2009; Turley-Ames & Whitfield, 2003) and computer-based WM training (Klingberg, 2010). WM strategy training can benefit children with reading difficulties (Swanson, Kehler, & Jerman, 2010) by either specifically helping with the reading process or by targeting general WM deficits (Turley-Ames & Whitfield, 2003). Computer-based WM training programs, such as Cogmed (Cogmed, 2006), consist of several demanding WM tasks that target a variety of components of WM, including verbal WM and visuospatial WM (Morrison & Chein, 2011). These programs focus on tasks that are general and encompass many parts of WM, rather than including specific strategies (Klingberg, 2010). Individuals are required to rapidly encode and retrieve items from WM, while the program adapts to ability level and progressively gets more difficult as gains are made. Computer-based WM training programs have been found to increase WM capacity, as well as improve attention (Klingberg et al., 2005; Klingberg, 2010; Morrison & Chein, 2011). Improvements have been noted in various components of WM, including visuospatial WM (Klingberg et al., 2005), visuospatial STM, verbal STM, visuospatial WM, and verbal WM (Holmes et al., 2010).

Improving WM has been correlated with reading improvement (Gustafson, Falth, Svensson, Tjus, & Heimann, 2011). For example, reading comprehension has been found to improve after individuals completed WM training (Chein & Morrison, 2010) and significant gains in single word and text reading ability have also been found (Loosli, Buschkuehl, Perrig, & Jaeggi, 2012). Further research into this area is warranted, given that WM improvements have been shown to transfer to other skills, such as reading (e.g., Chein & Morrison, 2010; Dahlin, 2010; Loosli et al., 2012). Examining the various components of WM before and after WM intervention may help to determine whether or not there are any differential effects on individuals with and without reading difficulties. In turn, exploring the effects of WM intervention on individuals with reading difficulties can assist in determining how WM and reading difficulties are related.

1.1 Statement of Purpose

Exploring the relationship between WM and individuals with reading difficulties is important in order to provide insight into which components of WM may be weaker in individuals with reading difficulties and whether or not WM interventions impact individuals with reading difficulties differently than individuals without reading difficulties. Currently, there is little research focusing specifically on reading difficulties and the various aspects of WM that may be involved. Furthermore, although there is an abundance of research on the effectiveness of WM training (e.g., Holmes, Gathercole & Dunning, 2009; Klingberg, 2010), only a small portion is focused on the effects of training on individuals with reading difficulties (e.g., Chein & Morrison, 2010; Loosli et al., 2012). Clearly, more research into this area is needed, so effective interventions can be found to better support the large number of children with reading difficulties. Therefore, the purpose of the current study was to further our understanding of the relationship between WM and reading ability and the impact that WM intervention has on individuals with reading difficulties.

Marche, McIntyre, and Claypool (2013) studied the improvement of memory ability and academic performance in children with WM deficits using computer-based and strategy-based WM training in a Social Sciences and Humanities Research Council (SSHRC) funded project. The current study used data from this larger project to conduct secondary data analysis to explore the relationship between WM and reading ability. This was accomplished by comparing the various components of WM, as determined by performances on various WM tasks, between individuals with and without reading difficulties. Specifically, this research explored the following research questions:

1. Are the WM profiles of individuals identified with reading difficulties different from those of individuals without reading difficulties? and
2. What are the differential effects of computer-based WM training on the WM profiles of children with and without reading difficulties?

1.2 Definitions

For the purpose of this paper, it is important to clarify the definitions of frequently used terms.

1.2.1 Working memory. WM refers to a system that is used for temporarily holding and manipulating information (Baddeley, 2010, Gathercole & Alloway, 2008). It plays a role in a variety of cognitive tasks such as reasoning, comprehension and learning. There are several different models proposed by researchers (i.e. Baddeley & Hitch, 1974; Cowan, 2010; Dehn, 2008; Kane et al., 2001), which divide WM into various components. The following components, proposed by Dehn (2008), are used in the current study: phonological short-term memory (which is also referred to as verbal short-term memory), verbal working memory, visuospatial short-term memory, visuospatial working memory, executive working memory, and long-term memory.

1.2.2 Working memory capacity. Refers to the limit on the amount of information that can be held or manipulated in working memory at a given time (Gathercole & Alloway, 2008).

1.2.3 Working memory profile. Refers to the particular strengths and weaknesses of an individual across the different sub-components of WM (i.e., phonological short-term memory, verbal working memory, etc.) (Gathercole & Alloway, 2008).

1.2.4 Reading difficulty. In this study, this is defined as below average reading ability. Individuals with reading difficulties may have word recognition problems, listening comprehension problems, or a combination of both (Catts, Hogan & Fey, 2003). In this study the existence of reading difficulties is determined by an individual's Reading Composite, Word Reading, and Sentence Comprehension standard scores on the Wide Range Achievement Test-4 (WRAT 4; Wilkinson & Robertson, 2006a).

1.3 Significance of Study

There is a relationship between academic achievement and WM, in areas such as reading and WM (De Jong, 1998; Engle et al, 1999; Swanson & Berninger, 1996; Swanson, 2000). The exploration of the relationship between WM and reading ability, by using the Automated Working Memory Assessment (AWMA; Alloway, 2007) as an assessment tool, is important because it will provide a clearer picture than previous research has shown of what aspects of WM may be correlated with reading difficulty, and to what degree any impairments may be noted (Swanson & Jerman, 2007). Exploring the relationship between computer-based WM interventions and reading ability may also illustrate any possible benefits that WM training may have on individuals with reading difficulties. In addition, this information may be used to explore effective interventions by determining which components of WM are weaker in individuals with reading difficulties, which components are most likely to be strengthened with WM interventions and thus which components should be targeted for intervention. This information is important in order to better support the large number of children with reading difficulties by offering more effective interventions and to address the impact poor reading ability can have on their lives (Milan, Hou & Wong, 2006).

1.4 Chapter Organization

A review of literature discussing the various components of WM and how they relate to academic learning and reading difficulties follows in Chapter 2. Chapter 3 includes a description of the research methods and procedure. The results of the study are described in Chapter 4. Finally, a discussion and analysis of the results, strengths and limitations of the current study and implications for future research are included in Chapter 5.

Chapter 2: Literature Review

The literature related to working memory has been critically reviewed and organized into four subsections. First, some of the models used to explain working memory are explored. Second, the concept of working memory capacity is considered. Third, working memory and its link to reading decoding and comprehension are described. Finally, some of the interventions used to improve working memory are examined.

2.1 Working Memory

Working memory (WM) is a system used for temporarily holding and manipulating information; it plays a role in various cognitive tasks such as reasoning, comprehension and learning (Baddeley, 1992, 2010). For example, when learning to read, WM helps individuals to hold on to the sounds letters make long enough to sound out new words. There are four key WM models that propose to explain the role and functions of WM: the WM model proposed by Baddeley and Hitch (1974), the *executive attention model* proposed by Engle and colleagues (Engle, 2002; Kane, Conway, Bleckley, & Engle, 2001), the *embedded-process model* proposed by Cowan (2005), and the *integrated model* of WM proposed by Dehn (2008). The integrated model of WM offers educators and psychologists a more complete understanding of the effects of WM deficiencies on individuals, thus, this model was used to guide the current study.

2.1.1 Working memory models. According to the model proposed by Baddeley and Hitch (1974), WM can be divided into three components; the *central executive* and two short-term storage systems: the *visuospatial sketchpad* and the *phonological loop*. The *central executive* controls attention and is responsible for regulating and coordinating the two short-term storage systems. The central executive controls the flow of information, transforming and manipulating information as needed, such as required in mental math problems (Baddeley, 1992; 2003). Whenever an individual must process and store information, the central executive is involved. It simultaneously selects strategies, controls attention, and integrates information from a variety of sources on separate tasks. In regards to attention, it can attend selectively to specific information while inhibiting irrelevant information, which can help monitor many complex cognitive processes. In terms of long term memory, the central executive is involved in activating and retrieving relevant information from storage, and forming associations between old information and new (Baddeley, 1992; 2003).

The *phonological loop* is responsible for manipulating language based information (Baddeley, 1992; 2003). It has two main features: a passive temporary storage component, in which verbal information is briefly held and spontaneously forgotten within a matter of seconds; and a subvocal articulatory rehearsal process, in which verbal information can be rehearsed and thus retained. Auditory stimuli, such as words, are registered in the order they are perceived and are quickly forgotten unless they are rehearsed. These perceptual stimuli are transformed into phonological codes which are matched with existing codes and meaning representations in long-term memory (Baddeley, 1992; 2003).

Phonological loop span is determined by both rate of decay and rate of rehearsal (Baddeley, 1992; 2003). The number of items capable of being temporarily stored in WM depends on the time taken to articulate them. Approximately 2 seconds of information can be rehearsed in the phonological loop. The number of words capable of being rehearsed depends on the length of the words and the time taken to articulate the words. Individuals with faster articulation rates can rehearse more words within the 2 second time frame, and thus remember more. Prior knowledge, as well as strategies such as chunking information, can also influence performance of WM; meaningful phonological information may aid short-term recall by activating relevant information from long term memory (LTM) (Baddeley, 1992; 2003).

Other variables that affect the functioning of the phonological loop include *similarity* as well as *recency* and *primacy* effects (Baddeley, 1992; 2003). Similarity effects refer to the fact that individuals have more difficulty recalling items that are similar sounding in nature. Similarity effects negatively affect the functioning of the phonological loop. Recency and primacy effects refer to the tendency to recall the first and last items of a list more easily than the middle items. Recent items are remembered because at the time of recall they are still retained in the phonological store. Items from the beginning of a list are possibly recalled more effortlessly, because the first item is repeated more often than subsequent items. Phonological memory span is correlated with cognitive functioning and academic learning, playing a role in language processing and literacy (Baddeley, 1992; 2003).

The *visuospatial sketchpad* is responsible for manipulating visual images and spatial information (Baddeley, 1992; 2003). It consists of two storage subcomponents: the visual subcomponent, which is responsible for the storage of static visual information, such as an object’s shape; and the spatial component, which is responsible for storage of information about motion and direction. It plays a role in generating and manipulating mental images, as well as aiding our physical movements, keeping us aware of where we are in our environment, in relation to other objects. It consists of a passive temporary store, as well as an active rehearsal process. Similar to phonological memory, recall is related to how long a stimulus is viewed, as well as the complexity of the stimulus, and decay takes place within a few seconds. When reading, printed letters and words are visually encoded and maintained, allowing individuals to keep their place in the text, as well as backtrack, if needed (Baddeley, 1992; 2003).

Visuospatial storage and rehearsal seem to depend, at least partly, on the phonological loop and articulatory rehearsal through recoding of visuospatial information into verbal information (Baddeley, 1992; 2003). However, the visuospatial sketchpad can operate independently. Rehearsal and retention can be negatively affected when stimuli can only be encoded visually, such as in cases where a verbal representation cannot be produced (Baddeley, 1992; 2003).

The *episodic buffer*, which was added more recently (Baddeley, 2010), is also controlled by the central executive, and integrates information from a variety of sources, such as visual and auditory information, with that of long term memory. It serves as a passive store that combines visual and auditory information into multidimensional representations or chunks. It has a limited capacity of about four episodes or chunks (Baddeley, 2010).

In the *executive attention model*, proposed by Kane, Engle and colleagues, WM is seen as an executive attention function (Engle, 2002; Kane, Conway, Bleckley, & Engle, 2001). They define this function as “an ability to effectively maintain stimulus, goal, or context information in an active, easily accessible state in the face of interference, to effectively inhibit goal-irrelevant stimuli or responses, or both” (Kane et.al., 2001, p. 180). In other words, important information is maintained by suppressing and inhibiting irrelevant and distracting information. This model is different from Baddeley’s model in that WM is seen as distinguishable from short-term memory. Kane, Engle and colleagues (2001) state that it is the ability to control attention in order to manage and recall relevant information that determines WM capacity, rather than short-term span. Dehn (2008) postulated that the executive attention model is different, yet not entirely inconsistent, with Baddeley’s model, which includes the central executive that controls attention. The difference between the two models is in regards to what determines WM capacity. While Baddely’s model claims that the phonological loop determines WM capacity, the executive attention model states that it is the ability to focus on relevant material and goals that determines WM capacity. The degree to which distracting information can be inhibited and relevant information can be actively maintained as the focus of attention is what determines individual differences in WM (Kane et al., 2001). The executive attention model also emphasizes the role of WM in retrieving and actively maintaining information from long-term memory (Engle, 2002; Kane et al., 2001).

The *embedded-process model* of memory, proposed by Cowan (1993, 2005), is also closely linked to long term memory. This model emphasizes the importance of attention, like the executive attention model, although it also focuses on levels of activation and expertise. “Short-term memory is represented as a nested subset of long-term memory. Specifically, the currently activated features comprise a subset of long-term memory, and the current focus of attention is in turn a subset of this activated memory” (Cowan, 1993, p. 162). The model distinguishes between activated memory features that are currently in the focus of attention and features that are considered to be outside of that focus (Cowan, 1993). The focus of attention can typically handle three to five chunks of activated information at a time thus restricting working memory retention and processing (Cowan, 2010). Dehn postulated that this model has some similarities to Baddeley’s model in that the amount of information capable of being held is dependent on the complexity of the information (Dehn, 2008). Items that are expected to be in the focus of attention are typically retrieved more quickly than other items, since retrieval is unnecessary (Dehn, 2008). Also, rather than splitting WM into multiple components (e.g., phonological loop, visuospatial sketchpad, central executive) like Baddeley’s model proposes, the embedded-process model considers “that transient, activated memory of various types (sensory, phonological, semantic, and motor) may be instances of a common, general storage medium with many dynamic properties and principles that are common across features types” (Cowan, 1993, p. 163).

***2.1.1.1 Integrated model of working memory*.** The *integrated model* of WM, which was built on Baddeley’s original WM model, is more relevant to academic learning, since it takes into consideration the challenges of measuring an individual’s WM ability and offers suggestions for interventions (Dehn, 2008). Dehn cited several concerns with current WM models, including: a lack of distinction between STM and WM (with many researchers using the terms interchangeably), not enough emphasis on the relationship between LTM and WM, and for those that do focus on LTM, the tendency to ignore the role of WM in STM and the process of encoding information into long-term memory. Furthermore, he claimed that some psychologists use definitions of WM that are too broad or that do not include enough distinction between executive functions and WM. In addition, limitations that are often placed on WM capacity are too small to encompass all of the information that is being processed at one point in time. The integrated model pulls together information from a variety of sources in an attempt to provide a model that is relevant to academic learning, and is useful to educators and psychologists who want a more complete understanding of the effects of WM deficiencies (Dehn, 2008). For these reasons, this study was guided by the integrated model.

In the integrated model of WM, all three forms of memory, STM, LTM, and WM, are seen as independent and are distinguishable from one another (Dehn, 2008). WM works with material held in both STM and LTM to encode, retrieve and store information in a passive manner. Since STM and LTM can also function on their own, they are not considered to be subsystems of WM. In the integrated model, WM is considered to be more closely linked to LTM than to STM because the main function of WM is to activate, retrieve, maintain and encode information that is taken from long-term storage. The emphasis on the relationship between LTM and WM is consistent with the embedded-process model (Cowan, 2005) and the executive attention model (Kane et al., 2001).

According to Dehn (2008), the integrated model of WM includes several components of memory: phonological/verbal STM, visuospatial STM, verbal WM, visuospatial WM, executive WM, long-term retrieval, WM operations, and activated LTM. The two types of STM are passive and they serve to briefly store information; phonological STM stores speech based information and visuospatial STM stores visual and spatial information. This version of STM is similar to Baddeley’s phonological loop and visuospatial sketchpad, but without the conscious rehearsal aspects. Dehn’s model considers the conscious rehearsal aspect to be a part of the executive WM. The WM components involve processing information from short-term storage or information that has been recently retrieved from long-term storage; verbal WM processes verbal information and visuospatial WM processes visuospatial information. Verbal and visuospatial WM are viewed as higher-level processing, while phonological and visuospatial STM are viewed as simple and passive. Executive WM involves coordinating and managing the various components, as well as inhibiting irrelevant memory items. WM is considered to have its own temporary storage capacity that is separate from STM. STM structures and processes are passive, instantaneous, and automatic, while WM structures and processes are active and conscious. Deficits in any one of the memory components may have an impact on learning (Dehn, 2008).

In the integrated model of WM, LTM is seen as an information storage system in which retrieval of information occurs automatically (Dehn, 2008). This differs from Baddeley's model in that STM information does not need to pass through WM in order to retrieve information from LTM. Instead, well entrenched information is seen to be automatically activated without requiring WM to become involved. Previous knowledge and skill affect the capacity and functioning of WM. Less processing is required for knowledge and skills that are firmly rooted in LTM. WM becomes involved when new information is presented, and it is necessary to actively search LTM in order to retrieve information to be restructured and encoded. "In addition to the several units (probably around four) that WM can process simultaneously, there is [a] large pool of activated long-term memory items and structures (located within long-term memory) to which WM has immediate access" (Dehn, 2008, p. 53). This pool of resources adds to the total WM capacity.

2.1.2 Working memory capacity. WM capacity refers to the limit on the amount of information that can be held in WM (Gathercole & Alloway, 2008) and no single factor determines WM capacity and performance (Dehn, 2008). Dehn stated that "there are most likely separate resources, with separate limits for storage and processing, while at the same time some shared general resources" (Dehn, 2008, p. 48). Cognitive factors, such as processing speed and the ability to control attention and inhibit interference may also impact WM capacity. Prior knowledge, practicing until items are mastered, and the utilization of strategies that aid memory may also have an impact on WM capacity by increasing the size of the memory chunks that are manipulated (Dehn, 2008).

2.1.2.1 Working memory capacity and academic achievement. WM capacity is related to academic achievement in a number of areas, including reading decoding, reading comprehension, spelling, vocabulary development, math calculations and math problem solving (Engle, Tuholski, Laughlin, & Conway, 1999; Swanson & Berninger, 1996; Swanson, 2000). WM capacity can differ among individuals in terms of how much information can be stored, as well as how effectively information can be processed (Dehn, 2008). Deficits in WM can have an impact on the acquisition of skills, knowledge and general cognitive functioning (Dehn, 2008). Children with low scores on WM capacity measures also have low scores on academic achievement measures (Gathercole & Alloway, 2008). The converse is also noted; children with high scores on WM capacity measures score high on academic achievement measures. These findings are consistent with young as well as older students (Gathercole & Alloway, 2008). Children with low WM capacity are generally easily distracted, tend to forget instructions, have difficulty with tasks requiring both storing and retrieving information, have difficulty keeping their place during assignments and often require extra help in the classroom (Alloway, Gathercole, Kirkwood, & Elliott, 2009).

WM is involved in many classroom learning activities, such as remembering and following instructions (Gathercole, Durling, Evans, Jeffcock, & Stone, 2008). Instructions can express sequences of actions in learning activities and can supply crucial information and important details often needed for detailed tasks (Gathercole & Alloway, 2008). Instructions can place heavy loads on WM, which often means that individuals with low WM capacity have a difficult time following them. Learning opportunities are often missed because individuals fail to complete tasks when detailed content, important to many classroom activities, is forgotten. For example, following multi-step instructions, such as copying a set of words from the board, writing a word that rhymes with the target word, and then writing a sentence that uses both words, can be difficult for children with low WM capacities. Not only are these children failing to complete the task at hand (i.e., remembering to write a sentence using both words), but they are also missing out on other learning opportunities, such as the additional writing opportunities presented. When observing children with poor WM in the classroom, it was discovered that “the WM failures observed had consequences for many different kinds of learning, ranging from the child’s developing facility with language through to knowledge and skills at handling print and numbers” (Gathercole & Alloway, 2008, p. 58).

Classroom activities often require students to complete tasks that require both memory storage and other cognitive processes (Gathercole et al., 2008). Individuals with poor WM often experience difficulties when stress is placed on WM by mental activities that require temporarily storing information in the mind while needing to retrieve additional information or while doing something else that is mentally challenging (Gathercole & Alloway, 2008). For example, when a student is asked to count the number of words in a sentence and then write it down, the task requires both storage (i.e., remembering the sentence) and mental processing (i.e., counting the words). The mental processing often demands full attention, making the storage and thus recall of information very difficult for individuals with low WM capacity.

Individuals with low WM capacities also have difficulty tracking their progress in activities (Gathercole & Alloway, 2008). Place-keeping, while completing a task, is especially important in young children who are just learning the skills they need for reading or math. For example, while copying notes from the board, children with poor WM may copy the beginning of one word with the ending of another word, often skipping words altogether. Individuals with low WM capacity often make repetition, skipping or counting mistakes, which arise when they fail to remember their place in a task (i.e., which word they were writing), and can lead to frequent errors in their work.

Individuals with poor WM do not fully engage in group discussions and are often reserved in large classroom activities, rarely volunteering information when questions are posed (Gathercole & Alloway, 2008). They are often described by teachers as appearing withdrawn and distracted, as well as having low levels of motivation, low self-esteem, short attention spans and high levels of frustration (Gathercole & Alloway, 2008). When activities are mentally challenging for students, they often struggle to maintain focus. Individuals with low WM capacities are more likely to experience lack of focus than individuals with average WM capacities, when engaged in demanding cognitive activities (Kane et al., 2007). Individuals with low WM capacity may have difficulty keeping all information necessary for the mental activity straight because their WM is so overloaded (Gathercole & Alloway, 2008). Often children with low WM capacity lose focus in activities only after they begin to make errors, which in some cases may be because of WM overload. Children with poor WM are also described by their teachers as being poor at monitoring the quality of their work. They frequently make careless mistakes, fail to check over their work before it is handed in, and produce unorganized and sloppy written work. While these errors can be caused by low academic ability, they can also be attributed to WM issues, such as forgetting crucial information and difficulty remembering and following the instructions.

This lack of basic skills can be attributed to low WM capacity and often has an impact on academic achievement. Children with poor WM generally achieve low scores on measures of reading and math (Gathercole & Alloway, 2008). For example, in math, children with low WM capacity often have difficulty learning to add, subtract, multiple and divide. These basic number skills are difficult to acquire given the load on WM that is required in order to learn them. Frequent errors and miscalculations are often the result. These skills require not only the storage of numerical information, but also the retrieval and application of number rules. Ineffectively learning these basic number skills also has the effect of slowing down the rate of learning for other more complex tasks. An individual with poor WM must often rely on simpler, less effective strategies, such as finger counting, rather than simply being able to retrieve previous knowledge that has already been learned well.

2.1.3 Working memory and reading. Difficulty learning to read is correlated with low WM capacity (De Jong, 1998), likely due to various demands of the reading process (e.g., decoding symbols, interpreting meaning). For example, multiple processes are needed for proficient text reading because information must be temporarily stored in WM while reading a sentence through to the end (Loosli, Bushkuehl, Perig, & Jaeggi, 2012). When individuals decode unfamiliar words, they must process new information while integrating it with what they already know (Dehn, 2008). These types of high demands on a limited resource pool make it difficult for children with low WM capacities to maintain information during reading (Swanson & Jerman, 2007).

In order to learn to read, children must learn to match letter combinations to sounds in language (i.e., phonics) as well as words with unique letter patterns (i.e., sight words) (Gathercole & Alloway, 2008). These patterns and combinations of letters and sounds are often learned more slowly by children with poor WM, which interferes with their ability to learn new vocabulary and gain basic reading and writing skills. This problem is amplified when these basic skills are needed in order to build on when learning new skills. When foundational skills are not learned well, it makes it more difficult for more complex reading and writing skills to be learned.

Reading comprehension is also affected by poor WM (Gathercole & Alloway, 2008). Words and sentences need to be held in temporary storage long enough for the meanings attached to these words to be retrieved. Individuals must store and retrieve these words, while also reading the text on the page, putting considerable strain on individuals with low WM capacity. Difficulty interpreting meaning from words and phrases leads to a poor understanding of what has been read.

***2.1.3.1 Research on working memory and reading difficulties*.** Although there is evidence of a relationship between WM and reading (e.g., De Jong, 1998; Swanson & Jerman, 2007), there is conflict in the literature regarding what components of WM, if any, are most likely involved in the reading process.

Several studies found that individuals with reading difficulties had deficits in verbal WM (e.g., Cohen-Mimran & Sapir, 2007; Compton, Fuchs, Fuchs, Lambert, & Hamlett, 2012; Booth, Boyle, & Kelly, 2014; De Jong, 1998; Nevo & Breznitz, 2013; Swanson & Jerman, 2007). The relationship between verbal WM and reading ability is seen in longitudinal studies (e.g., Compton et al., 2012), as well as in studies involving languages other than English (e.g., Cohen-Mimran & Sapir, 2007; D'Amico, 2011).

Some studies found that individuals with reading difficulties also had deficits in verbal STM (e.g., Cohen-Mimran and Sapir, 2007; Wang & Gathercole, 2013), while others did not find deficits in verbal STM (e.g., De Jong, 1998; Nevo & Breznitz, 2013; Swanson & Jerman, 2007). In a study which looked at the development of WM ability, Nevo and Breznitz (2013) found that overall WM capacity improved significantly in a group of grade one students, compared to their WM capacity a year earlier, when they were in Kindergarten. However, when the group was split according to reading decoding skills, it was noted that individuals with reading difficulties had lower WM ability overall. Furthermore, it was found that verbal WM, compared to verbal STM and visuospatial STM, was most highly correlated with reading skills (Nevo & Breznitz, 2013). Visuospatial WM was also correlated to reading skills, but to a lesser degree.

Many studies did not look at all components of WM. For example most did not assess visuospatial STM or visuospatial WM. A few studies that did assess all components of WM found that individuals with reading difficulties also had low visuospatial STM and visuospatial WM capacity (e.g., Pham & Hasson, 2014; Wang & Gathercole, 2013; Gathercole, Alloway, Willis, & Adams, 2006). Wang and Gathercole (2013) and Gathercole et al. (2006) found that children with reading difficulties scored significantly lower on all measures of memory, compared to children without reading difficulties. In a study of WM as a predictor of children's reading ability, Pham and Hasson (2014) found that reading ability correlated to all WM tasks administered (i.e., verbal STM, visuospatial STM, verbal WM, visuospatial WM). They also found that verbal WM tasks were correlated with overall reading skills, while visuospatial WM tasks were correlated with reading comprehension skills, but not reading fluency skills (Pham & Hasson, 2014).

Not all research showed a relationship between reading difficulties and WM impairment (i.e., Bayliss, Jarrold, Baddeley, & Leigh, 2005; Pickering & Gathercole, 2004; Van der Sluis, Van der Leij, & De Jong, 2005). Some studies did not find any difference between WM performance in individuals with reading difficulties and individuals without reading difficulties. Children with reading difficulties performed within the normal range (low average levels) in all areas of WM (Pickering & Gathercole, 2004), and no WM deficits were found (Van der Sluis et al., 2005). Although children with reading difficulties were not found to have WM impairments, children with difficulties in both reading and math performed lower on tasks of verbal WM (Pickering & Gathercole, 2004), as well as verbal STM and visuospatial STM (Pickering & Gathercole, 2004; Van der Sluis et al., 2005). Bayliss and colleagues (2005) found that WM performance was related to word reading skills in typically developing children, but was not correlated with reading ability in children with learning difficulties. Bayliss and colleagues suggested that the performance of individuals with learning difficulties reflected WM limitations different from those of typically developing individuals. WM performance appeared to be constrained by individual differences in STM and processing speed in the typically developing group and only STM, and not processing speed, accounted for individual differences in individuals with learning difficulties. Individuals with learning difficulties and typically developing individuals also appeared to achieve comparable levels of WM performance at different rates and in different ways. It is conjectured that individuals with learning difficulties and typically developing individuals use different strategies in order to store and process information (Bayliss et al., 2005).

These incongruities in the literature point to the need for further research in this area. Some of the differences found in the literature can be explained by the use of non-standardized tests to assess WM. Specifically, some studies used measures to assess WM that were designed for the study, but were not standardized measures and thus not based on population norms (e.g., Bayliss et al., 2005). Furthermore, several studies used a variety of measures from different sources (i.e., WISC, WJ-III) in order to assess the different components of WM (e.g., Pham & Hasson, 2014; Van der Sluis et al., 2005). Also, several studies only looked at one component of WM (i.e., verbal WM) even though other components of WM have been shown to be correlated to reading difficulties (e.g., Wang & Gathercole, 2013). Additionally, several studies assessed individuals in languages other than English (e.g., Cohen-Mimran & Sapir, 2007; D'Amico, 2011; De Jong, 1998; Nevo & Breznitz, 2013; Van der Sluis et al., 2005) and different languages may have an impact on an individual's ability to learn to read, as well as on the components of WM that are involved.

The current study utilized the Automated Working Memory Assessment (AWMA) since it aligned most closely with Dehn's integrated model of WM (Dehn, 2008). This assessment tool was developed by Alloway (2007) and is a computer-based assessment of WM capacity that aims to identify WM deficits in individuals aged four to 22. One of the main benefits of the AWMA is that it differentiates between STM and WM components. Furthermore, it is one of the only memory scales that separately measures visuospatial WM and verbal WM. This is beneficial when trying to determine which components of WM are most related to reading difficulties. The use of the AWMA provided more continuity between assessment measures by using the AWMA rather than a variety of separate measures. This provided a more reliable basis with which to compare performance on memory tasks that measure different components of memory. Another benefit to using the AWMA is that it has been standardized, which strengthened the measure statistically (Alloway, 2007). Furthermore, by assessing English speaking Canadian children, the results may be more generalizable to the local population.

There is a need for research that explores the various WM components in children with and without reading difficulties, so that strengths and weaknesses can be determined and effective interventions for individuals with WM deficits and reading difficulties can be developed. Before WM interventions are recommended to individuals with reading difficulties it is important to determine if they would be beneficial. Exploring the WM profiles of individuals with and without reading difficulties after they have completed a WM intervention program would help to determine whether or not there are any differential effects on the components of WM between these two groups of individuals. This information would help to inform researchers and educators on whether or not it is possible to increase WM capacity, which components of WM may be affected, whether any of the components of WM are affected to a greater or lesser degree, and whether or not any of the changes are different for individuals with or without reading difficulties.

2.1.4 Working memory interventions. Reading improvements have been correlated with improved WM, suggesting that targeting the improvement of WM may complement traditional reading interventions (i.e., phonological and comprehension training) (Gustafson, Falth, Svensson, Tjus, & Heimann, 2011). In addition, improved WM may make the learning experience more rewarding (Gustafson et al., 2011). WM is an important factor in academic achievement, and even small increases in WM capacity may improve children's performance (Minear & Shah, 2006). Given the relationship between WM and academic achievement and functioning, exploring strategies that purportedly improve WM may be beneficial, since a deficit in WM may prevent children with learning disabilities from responding well to traditional interventions (Dehn, 2008). Additionally, exploring the effects that WM interventions have on the different components of WM can help to further our understanding of the relationship between WM and reading. Furthermore, it can help to determine the feasibility of using WM interventions to assist in improving reading ability.

Two interventions used to improve WM are strategy training (Morrison & Chein, 2011; Turley-Ames & Whitfield, 2003) and computer-based WM training (Klingberg et al., 2005; Klingberg, 2010; Morrison & Chein, 2011). Strategy training interventions, such as chunking, mnemonics and imagery, can be used to improve WM (Dehn, 2008). Strategy training techniques, which teach methods to help process and store information (Morrison & Chein, 2011; Turley-Ames & Whitfield, 2003), have been shown to boost academic performance (Holmes, Gathercole & Dunning, 2009; Holmes et al., 2010; Klingberg, 2010). For example, WM strategies can be used as interventions to help with reading difficulties either by targeting general WM deficits, or by specifically helping with the reading process. Although many learners develop and use strategies on their own, individuals with learning disabilities are less likely to do so, possibly because of an inability to use strategies correctly or because of a WM deficit (Dehn, 2008). The focus of strategy based training is to improve WM performance, whether the origin of the poor performance is low WM capacity, or lack of strategy knowledge or strategy use.

Several studies showed that increased WM capacity was related to the use of strategy training (e.g., McNamara & Scott, 2001; Minear & Shah, 2006). Turely-Ames and Whitfield

(2003) found that strategy training was beneficial to students with low WM capacity, although they were slower to learn the strategies than students with high WM capacity. Children with reading difficulties also benefited from strategy training, especially cued and rehearsal training (Swanson, Kehler, & Jerman, 2010). While strategy training was shown to be beneficial, the addition of interventions, such as computer-based WM training (Klingberg, 2010), may be even more effective.

2.1.4.1 Computer-based working memory training. New research is beginning to reveal that it is possible to increase WM capacity, as well as other cognitive skills, through computer-based WM training (e.g. Klingberg et al., 2005; Klingberg, 2010; Morrison & Chein, 2011). These types of training programs typically consist of several demanding WM tasks that target a variety of components of WM, such as verbal WM and visuospatial WM (Morrison & Chein, 2011). These programs do not generally include specific strategies, but focus on tasks that are more general and encompass many parts of WM. Computer-based WM training programs are demanding and require individuals to rapidly encode and retrieve items from WM, and recall items in the face of interference. Programs typically adapt to an individual's ability level and progressively get more difficult as the individual makes gains (Morrison & Chein, 2011).

The developers of one such program, Cogmed, claimed that increased WM capacity, as well as increased attention, is correlated with the completion of computer-based WM training (Klingberg, 2010). The program drew from research on neuroplasticity principles to WM training, as well as on the role of WM deficits on various learning disabilities and psychiatric disorders (Roche & Johnson, 2014). The Cogmed program is tailored for three different age groups: Cogmed JM for preschool children (ages 4-6), Cogmed RM for school-aged children (ages 7-18), and Cogmed QM for adults (Cogmed, 2006; Roche & Johnson, 2014). Each program shares the same WM tasks, but with different, age-appropriate, interfaces. The Cogmed RM program is space-themed and consists of 25 computer training sessions, lasting approximately 30-45 minutes (Cogmed, 2006). It involves repeated performance of WM tasks which are adapted to an individual's performance. Difficulty is increased by adding more targets, having longer training sequences, and completing more complex tasks (Roche & Johnson, 2014). Each session includes several tasks that each target different components of WM. Training days are concluded with the opportunity to play a motivational racing game in order to provide incentive and reward for staying on task (Roche & Johnson, 2014). Sessions take place in a school or office setting and are overseen by a trained coach who provides support, feedback, motivation and structure (Cogmed, 2006).

2.1.4.1.1 Effectiveness of working memory training. Numerous studies have looked at the effects of computer-based WM training on individuals affected with Attention Deficit Hyperactivity Disorder (ADHD) and Learning Disabilities (LD) (e.g., Holmes et al., 2010; Klingberg et al., 2005). Some have reported improvements in visuospatial WM (e.g., Klingberg et al., 2005), in verbal WM and visuospatial WM (Gropper, Gotlieb, Kronitz, & Tannock, 2014), in visuospatial STM and verbal WM (Gray et al., 2012), and in all components of WM (verbal STM, visuospatial STM, verbal WM, and visuospatial WM) (Holmes et al., 2010). Furthermore, WM training was related to self-reported improvements in ADHD symptoms (Gropper et al., 2014). WM training was also correlated with positive results, such as improved WM, improved information processing, less depressive symptoms and less anxiety, in individuals with impaired WM due to acquired brain injury (Akerland, Esbjornsson, Sunnerhagen, & Bjorkdahl, 2013). The effects of computer-based WM training on the academic achievement of individuals with ADHD and LD is less clear. Gray and colleagues (2012) and Gropper and colleagues (2014) found that academic achievement, as assessed by standardized tests of reading and math achievement, was not related to WM training.

Increasing WM through training was also related to improvements in the cognitive skills of individuals in non-clinical populations (e.g., Holmes, Gathercole, & Dunning, 2009; Morrison & Chein, 2011). Holmes and colleagues (2009) found that WM training was related to an improvement in all aspects of WM in children with low WM ability. Gains were greatest for tests involving visuospatial STM, visuospatial WM and verbal WM (Holmes et al., 2009). WM training was not related to an increase in post-training scores of academic achievement, although there was a relationship between WM training and improved math performance at the 6 month follow-up. The authors suggested that cognitive improvement caused by WM training would likely take a while to significantly impact academic performance (Holmes et al., 2009). Greater academic progress in math and English (including reading and writing skills), as determined by curriculum assessments, was noted when WM training was administered by teachers within a school setting (Holmes & Gathercole, 2014). This indicates that WM training has the potential to transfer to academic ability.

2.1.4.1.2 Working memory training and reading improvement. WM training has been shown to be correlated to improvements in reading decoding (Loosli et al., 2012) and reading comprehension (Chein & Morrison, 2010; Dahlin, 2010). The authors postulated that this could be because the attentional control of the participants was facilitated by the WM training. Dahlin (2010) examined the relationship between WM and reading achievement in primary school-aged children with special education needs and found that WM training was related to increases in children's WM. WM measures were found to be related to word reading and reading comprehension. Furthermore, the effects of WM training seemed to be beneficial to the development of reading comprehension. While there was a significant correlation between WM training and improved performance on the reading comprehension task, it was not significantly correlated to enhanced performance on tasks of word decoding or orthographic knowledge. Dahlin (2010) suggested that WM, including verbal WM and visuospatial WM, plays a central role in reading comprehension. Furthermore, although Foy and Mann (2014) found that WM training was not related to any direct effects on the pre-reading skills of children of low socioeconomic status, they postulated that WM training may indirectly benefit children at risk for reading difficulties by helping them get the most out of instruction opportunities through self-regulation and memory skill development.

2.1.4.1.3 Working memory training research. Some research has shown that WM training and increased WM ability are significantly related, and WM training has also been found to be related to positive effects on other skills, such as reading (i.e., Chein & Morrison, 2010; Dahlin, 2010; Foy & Mann, 2014; Holmes & Gathercole, 2014; Loosli et al. 2012). A review of the literature has shown that different aspects of reading and different components of memory are found to be affected in various studies.

Some researchers claimed that computer-based WM training is only related to improved performance on tasks that directly resemble training (Shipstead, Hicks, & Engle, 2012) and that there is no evidence that the improvements are lasting (Melby-Lervag & Hulme, 2013). However, other researchers have stated that there is sufficient evidence to support the claim that WM training is related to a significant increase in visuospatial WM and verbal WM, as well as attention (Shinaver, Entwistle, & Soderqvist, 2014). Despite the optimism surrounding computer-based WM training programs, additional research is needed in order to sufficiently support many of the claims (i.e., improved cognition and academic achievement) (Morrison & Chein, 2012).

2.2 Importance of Current Study

In order to discover if WM interventions may be effective for individuals with reading difficulties, it is important to first understand what WM components may be involved (e.g., Dehn, 2008, Gathercole et al., 2006). Looking at the WM profiles of children with and without reading difficulties, in relation to interventions such as computer-based WM training, can help us to understand the relationship between WM and reading (e.g., Chein & Morrison, 2010, Dahlin, 2010, Loosli et al., 2012). The questions posed in the current study explored whether or not there were any differences in the WM profiles of individuals with or without reading difficulties before and after a WM intervention program had been completed. The results of this research will help to determine whether or not the WM profiles of individuals with reading difficulties are more fixed or changeable than those of individuals without reading difficulties. This research will also help to determine whether or not there are differences in the amount of change that occurs between the two groups. Furthermore, this research will help to determine whether or not certain components of WM are more likely to change after WM interventions and if these changes are different in individuals with reading difficulties versus those without reading difficulties. Although the results from the small local sample used in this study are not generalizable to all students, they can be useful as a starting point to consider how WM affects students with reading difficulties.

Chapter 3: Methodology

3.1 Nature of the Study

In a Social Sciences and Humanities Research Council (SSHRC) funded project, Marche, McIntyre, and Claypool (2013) studied the improvement of memory ability and academic performance in children with Working Memory (WM) deficits using computer-based and strategy-based WM training. In the primary study, each child completed four subtests from the Automated Working Memory Assessment (AWMA; Alloway, 2007), followed by the *block design*, *vocabulary,* and *matrix reasoning* subtests of the Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV; Wechsler, 2003), the *visual-auditory learning, retrieval fluency,* and *decision speed* subtests of the Woodcock Johnson Tests of Cognition-Third Edition (Woodcock, McGrew, & Mather, 2001a), the reading (*word reading* and *sentence comprehension*) and math subtests from the Wide Range Achievement Test-4 (WRAT4; Wilkinson & Robertson, 2006a), and the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007). Measures relevant to the current study, specifically the AWMA and the WRAT, were used to conduct secondary data analysis in order to explore the relationship between WM and reading ability. Specifically, this study addressed the following research questions:

1. Are the WM profiles of individuals identified with reading difficulties different from those of individuals without reading difficulties? and
2. What are the differential effects of computer-based WM training on the WM profiles of children with and without reading difficulties?

3.2 Participants

The data of 63 students (35 males and 28 females) from two urban school divisions in Saskatchewan was used for this study. Participants ranged in age from 7 to 14 years old (Grades 1-9); the average age was 10.43 and the median age was 11. They were voluntarily recruited for participation in the primary study, from which the data for this study was obtained, using posters and notices in school newsletters. The parents of all of the participants gave their informed consent, and the participants gave their informed assent at the pre-training sessions.

3.3 Instrumentation

3.3.1 Automated Working Memory Assessment (AWMA). The AWMA consists of 12 subtests which assessed phonological/verbal short-term memory (STM), verbal WM, visuospatial STM and visuospatial WM (Alloway, 2007). All tasks are computerised and are administered using a span procedure, beginning at the easiest level (i.e., one or two items) and increasing by one if four out of the six lists are completed correctly. Trials are discontinued when three errors occur at one level. Instructions and verbal stimuli are presented orally through a recording on a computer. The test-retest reliability for the subtests of the AWMA range from .69 to .90 (Alloway, 2007). The AWMA has good diagnostic validity and is highly consistent with the *working memory index* of the WISC-IV (Alloway, Gathercole, Kirkwood, & Elliott, 2008).

In the current study, the standard scores from four of the subtests of the AWMA were used to assess verbal STM, visuospatial STM, verbal WM, and visuospatial WM; *digit recall, dot matrix, backwards digit recall*, and *Mister X*, respectively (Alloway, 2007). The *digit recall* subtest involved recalling a sequence of numbers that were presented verbally by the computer at a rate of one per second, in the order in which they were presented. The *dot matrix* subtest required individuals to view a sequence of dots that appeared in the squares of a 4 by 4 matrix and then to point, in correct order, to the squares in which they appeared. In the *backwards digit recall* subtest, verbally presented numbers were required to be recalled in reverse order. In the *Mister X* subtest, individuals were presented with two figures of men (Mr. X's), one with a yellow hat and one with a blue hat, each with a ball in one of their hands (Alloway, 2007). The Mr. X with the blue hat appeared rotated in one of six possible positions. Individuals were asked to say whether the Mr. X with the blue hat was holding the ball in the same hand as the Mr. X in the yellow hat. At the end of each list, the individual was asked to point to the location of the ball that the Mr. X with the blue hat was holding, in the order that they were seen (Alloway, 2007).

3.3.2 Wide Range Achievement Test (WRAT 4). The Wide Range Achievement Test (WRAT 4) consists of four subtests which measure basic academic skills, including math computation, spelling, and reading (Wilkinson & Robertson, 2006a). This study utilized the data from the *word reading* and the *sentence comprehension* subtests. Standard scores from the two reading subtests are combined to create a *reading composite* score. The *word reading, sentence comprehension* and *reading composite* scores are used in the data analysis. The subtest reliability coefficients for the WRAT 4 are excellent and range from .80 to .90, with the median alpha reliability coefficient for the *reading composite* ranging from .95 to .96 (Wilkinson & Robertson, 2006b). The validity of the WRAT 4 ranges from moderate to highly moderate

(Wilkinson & Robertson, 2006b). The WRAT 4 *sentence comprehension* subtest correlations with other subtests are moderate (e.g., WJ-III Reading Comprehension, .60; Woodcock, McGrew, & Mather, 2001b). Likewise, the WRAT 4 *word reading* subtest correlations with other measures of word recognition are also moderate (e.g., WJ-III Basic Reading, .66; Woodcock, McGrew, & Mather, 2001b). The WRAT 4 *reading composite* score correlates to a moderately high level with the *broad reading composite* from the WJ-III (.73; Wilkinson & Robertson, 2006b).

In the *word reading* subtest, which assessed word decoding and recognition, individuals were asked to read aloud words of increasing difficulty (Wilkinson & Robertson, 2006). In the *sentence comprehension* subtest, individuals were asked to read a short passage to themselves and were then required to identify a missing word (modified cloze technique).

3.4 Procedure

In the primary SSHRC study from which the data for this study was obtained, WM capacity, cognitive ability, and academic achievement were assessed at both pre-training and post-training sessions. Each child completed the assessments individually, in a single session. Assessment sessions were completed in a quiet, distraction free room and lasted approximately 2 hours. Upon completion of the pre-training session, the participants in the primary study were randomly assigned to one of four groups; *Strategy* training, *Cogmed* training, *Strategy + Cogmed* training, and a *Control* group. For the purposes of the current study, post-training data from the *Cogmed* group and the *Control* group were utilized. The *Cogmed* training group participated in the Cogmed program (Cogmed, 2006) for 30 to 45 minutes, five times a week, for five weeks. The *Control* group was assessed at both pre and post-testing, which were 6 weeks apart, but did not participate in any training.

3.5 Data Analyses

Data were analyzed using the Statistical Package for the Social Sciences 20.0 (IBM Corp., 2013) for Windows once post-training data was obtained for analyses.

3.5.1 Research question 1. In order to answer the first research question, which addressed whether or not there were differences in the WM profiles of individuals with and without reading difficulties, participants were split into two groups. The WRAT 4 reading composite standard scores of all 63 participants were divided into two groups using a median split (i.e., independent variables; reading difficulty group and average reading ability group).

The two groups were then analyzed using a series of one-way analysis of variance (ANOVA) tests, which compared the pre-training AWMA subtest standard scores (i.e., dependent variables; verbal STM, visuospatial STM, verbal WM, and visuospatial WM standard scores) of both reading groups.

3.5.2 Research question 2. In order to answer the second research question, which addressed the differential effects computer-based WM training had on the WM profiles of children with and without reading difficulties, independent samples t-tests were run. First, the post-training AWMA subtest standard scores (i.e., dependent variables; verbal STM, visuospatial STM, verbal WM, and visuospatial WM) of 14 participants in the *Cogmed* group and 14 participants in the *Control* group (i.e., independent variables; *Cogmed*, *Control*) were compared in order to determine if there were any differences between the two groups. Subsequently, independent samples t-tests were completed in order to determine whether there were differences between the post-test WM profiles of children with and without reading difficulties in each experimental group (i.e., independent variables; *Cogmed*/reading difficulty group, *Cogmed*/average reading ability group, *Control*/reading difficulty group, *Control*/average reading ability group). Specifically, the post-training AWMA subtest standard scores (i.e., dependent variables; verbal STM, visuospatial STM, verbal WM, and visuospatial WM) were compared across each experimental group.

Further analyses were performed in order to determine whether or not WM training had a differential effect on individuals with average reading ability compared to individuals with reading difficulties. Specifically, the pre-training and post-training AWMA subtest standard scores (i.e., dependent variables; verbal STM, visuospatial STM, verbal WM, and visuospatial WM) of children with and without reading difficulties in each experimental group (i.e., independent variables; *Cogmed*/reading difficulty group, *Cogmed*/average reading ability group, *Control*/reading difficulty group, *Control*/average reading ability group) were compared to determine if any differential effects were noted.

Chapter 4: Results

The relationship between working memory (WM) and individuals with reading difficulties were explored in the current study using secondary data analyses on data collected from 63 students (35 males and 28 females) in two urban school divisions in Saskatchewan with and without reading difficulties participating in a larger SSHRC funded study (March et al. 2013). Specifically, data were analyzed in order to provide insight into which components of WM may be weaker in individuals with reading difficulties and whether or not WM interventions impact individuals with reading difficulties differently than individuals without reading difficulties.

4.1 Relationship between Working Memory and Reading Difficulties

The first research question posed was: Are the WM profiles of individuals identified with reading difficulties different from those of individuals without reading difficulties? Descriptive statistics for the WM and reading ability measures at pre-test were completed in order to provide a summary of the data and in order to determine the distribution of the data (see Table 1).
In order to determine if the WM profiles of individuals with reading difficulties were different from those of individuals without reading difficulties, participants were divided into two reading ability groups using the reading standard scores of the WRAT 4 (Wilkinson & Robertson, 2006). All three measures of reading on the WRAT 4, *word reading*, *sentence comprehension*, and *reading composite* (which is a combination of the *word reading* and *sentence comprehension* scores) were used to determine reading ability. All three measures were used in order to determine whether or not the method of determining reading ability differentially affected the results on all of the WM measures. Furthermore, the subtests that composed the reading composite were examined separately in order to determine whether or not individual scores provided a different profile than looking at both scores together.

First, data were screened for outliers. Participant's scores were converted to standardized z scores. Any participants with values ≥ +/- 1.96 for any of the reading standard scores were excluded from the analysis using that variable. Specifically, four participants were excluded from the *reading composite* measure, five participants were excluded from the *word reading* measure, and two participant was excluded from the *sentence comprehension* measure. After outliers were excluded, reading ability groups were determined using a median split in order to

Table 1

Summary of Mean, Standard Deviation (SD), Range, and Median for WM and Reading Measures at Pre-test

WM Component	Mean	SD	Range	Median
Verbal STM	95.76	13.02	64-137	96.00
Visuospatial STM	103.78	18.04	66-143	101.00
Verbal WM	97.06	16.37	58-143	93.00
Visuospatial WM	101.75	17.94	70-144	98.00
Word Reading	94.89	13.40	68-138	93.00
Sentence Comprehension	97.02	15.99	65-144	96.00
Total Reading Ability	95.03	14.34	69-142	95.00

Note. n = 63

create groups with equal cell sizes. The median for the *reading composite* group was 94; participants with a standard score ≥ 94 were placed in the *average reading ability* group (i.e., individuals without reading difficulties) and those with a standard score ≤ 93.5 were placed in the *reading difficulty* group (i.e., individuals with reading difficulties). The median for the *word reading* group was 93; participants with a standard score ≥ 93 were placed in the *average reading ability* group and those with a standard score ≤ 92 were placed in the *reading difficulty group*. The median for the *sentence comprehension* measure was 96; participants with a standard score ≥ 96 were placed in the *average reading ability* group and those with a standard score ≤ 95 were placed in the *reading difficulty* group.

In order to determine if there were significant differences between the *average reading ability* group and the *reading difficulty* group on the pre-training session standard scores of the AWMA subtests, a series of one-way analysis of variance (ANOVA) tests were computed. The series of ANOVAs examined each of the four AWMA subtest scores and compared the scores of individuals with average reading ability to the scores of individuals with reading difficulties. Data were analysed using the between-subjects groupings described above. Given that the median split did not always result in equal cell sizes, data was randomly removed by deleting the appropriate number of data from analysis in order to make equal groups. For the *word reading* measure the data from two individuals from the *average reading ability* group were randomly deleted, and for the *sentence comprehension* measure the data from three individuals from the *average reading ability* group were randomly deleted.

4.1.1 Reading composite. Descriptive statistics for the *average reading ability* group and the *reading difficulty* group, when reading ability was split by the *reading composite* scores, were calculated for the WM measures in order to provide a summary of the data (see Table 2). For the reading composite measure, which looks at both word reading and sentence comprehension scores together, the ANOVA showed that there were differences in the scores of individuals with average reading ability and the scores of individuals with reading difficulty. Specifically, for verbal WM, individuals in the *reading difficulty* group had significantly poorer scores than individuals in the *average reading ability* group, $F\ (1, 57) = 4.97$, $p = .030$, $\eta_p^2 = .081$, $\beta = .591$. For verbal STM, $F\ (1, 57) = 2.96$, $p = .091$, $\eta_p^2 = .050$, $\beta = .394$, visuospatial STM, $F\ (1, 57) = 1.45$, $p = .234$, $\eta_p^2 = .025$, $\beta = .219$, and visuospatial WM, $F\ (1, 57) = .688$, $p = .410$, $\eta_p^2 = .012$, $\beta = .129$, no differences were found.

4.1.2 Word reading. Descriptive statistics for the *average reading ability* group and the *reading difficulty* group, when reading ability was split by the *word reading* scores, were calculated for the WM measures in order to provide a summary of the data (see Table 3). When reading ability was determined by scores on the WRAT 4 word reading subtest, no differences were found for verbal STM, $F\ (1, 55) = .820$, $p = .369$, $\eta_p^2 = .015$, $\beta = .144$, visuospatial STM, $F\ (1, 55) = .175$, $p = .677$, $\eta_p^2 = .003$, $\beta = .070$, verbal WM, $F\ (1, 55) = 3.09$, $p = .085$, $\eta_p^2 = .054$, $\beta = .408$, or visuospatial WM, $F\ (1, 55) = .107$, $p = .745$, $\eta_p^2 = .002$, $\beta = .062$.

4.1.3 Sentence comprehension. Descriptive statistics for the *average reading ability* group and the *reading difficulty* group, when reading ability was split by the *sentence comprehension* scores, were calculated for the WM measures in order to provide a summary of the data (see Table 4). For verbal STM, individuals in the *reading difficulty* group had significantly poorer scores than individuals in the *average reading ability* group, $F\ (1, 57) = 7.99$, $p = .007$, $\eta_p^2 = .125$, $\beta = .793$. For verbal WM, individuals in the *reading difficulty* group had significantly poorer scores than individuals in the *average reading ability* group, $F\ (1, 57) = 13.90$, $p < .001$, $\eta_p^2 = .199$, $\beta = .956$. For visuospatial WM, individuals in the *reading difficulty* group had significantly poorer scores than individuals in the *average reading ability* group, $F\ (1, 57) = 6.21$, $p = .016$, $\eta_p^2 = .100$, $\beta = .688$. No differences were found for visuospatial STM, $F\ (1, 57) = 1.88$, $p = .175$, $\eta_p^2 = .033$, $\beta = .271$.

Table 2

Summary of Mean, Standard Deviation (SD), and Range for WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Reading Composite Standard Scores)

	Average Reading Ability [a]			Reading Difficulty [b]		
WM Component	Mean	SD	Range	Mean	SD	Range
Verbal STM	97.07	11.29	71-124	91.86	11.29	64-112
Visuospatial STM	106.66	18.86	73-143	101.07	16.45	66-132
Verbal WM	99.00	15.18	69-124	90.86	12.49	58-117
Visuospatial WM	103.52	15.87	79-137	99.72	18.83	70-137

Note. [a] *n* = 29, [b] *n* = 29

Table 3

Summary of Mean, Standard Deviation (SD), and Range for WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Word Reading Standard Scores)

	Average Reading Ability [a]			Reading Difficulty [b]		
WM Component	Mean	SD	Range	Mean	SD	Range
Verbal STM	96.75	13.87	71-137	93.57	12.36	64-124
Visuospatial STM	105.04	18.82	73-143	102.96	18.24	66-138
Verbal WM	99.57	16.69	69-143	92.25	14.40	58-122
Visuospatial WM	101.36	18.39	70-137	99.86	15.82	71-133

Note. [a] *n* = 28, [b] *n* = 28

Table 4

Summary of Mean, Standard Deviation (SD), and Range for WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Sentence Comprehension Standard Scores)

	Average Reading Ability [a]			Reading Difficulty [b]		
WM Component	Mean	SD	Range	Mean	SD	Range
Verbal STM	101.00	13.88	71-137	91.90	10.40	64-112
Visuospatial STM	106.45	19.20	66-143	100.03	16.27	69-132
Verbal WM	104.72	15.45	86-143	90.14	14.325	58-120
Visuospatial WM	107.38	17.60	76-144	96.07	16.96	70-137

Note. [a] *n* = 29, [b] *n* = 29

4.2 Effect of Working Memory Training on Individuals With and Without Reading Difficulty

Analyses were also completed to answer the second research question: What are the differential effects of computer-based WM training on the WM profiles of children with and without reading difficulties? Prior to evaluating this second research question, independent samples t-tests were run between the *Cogmed* and *Control* group participants' pre-test scores. No significant differences were found between those assigned to the *Control* group or those assigned to the *Cogmed* group at pre-test, all *t*s < 1.58, *p*s > .14 indicating that the random assignment procedure was effective in ensuring there were no differences among participants at the outset. Independent samples t-tests were also run between the *Cogmed* and *Control* group participants' post-test scores to determine if there were any differences between the two conditions at post-test. It was found that individuals in the *Cogmed* group had higher scores on the verbal STM and verbal WM measures than individuals in the *Control group*, *t* (25) = -2.97, *p* = .006 and *t* (25) = -2.14, *p* = .043, respectively. No significant differences between groups were noted on the subtest scores for the visuospatial STM or visuospatial WM; *t* (25) = -1.23, *p* = .230 and *t* (25) = -1.62, *p* = .118, respectively.

Some significant differences between the *Cogmed* and *Control* group were noted in the post-test results, therefore additional analyses were computed. Specifically, in order to determine whether Cogmed training had any differential effects on the WM components of individuals with average reading ability compared to individuals with reading difficulties, independent samples *t*-tests were completed. Specifically, independent samples *t*-tests compared individuals with average reading ability and individuals with reading difficulty on post-training session AWMA subtest standard scores of the participants in the *Cogmed* group and of those in the *Control* group. Again, previously created groupings for all three measures of reading on the WRAT 4, *word reading*, *sentence comprehension,* and *reading composite,* were used to determine reading ability.

4.2.1 Reading composite. Reading ability was first determined by *reading composite* scores on the WRAT 4 and independent samples *t*-tests were run. Descriptive statistics of post-test WM scores for individuals in the *Cogmed* and *Control* groups, with and without reading difficulties, when reading ability is split by *reading composite* standard scores were calculated (see Table 5). These descriptive statistics were computed in order to provide a summary of each group of data and in order to determine the distribution of the data for the groups.

4.2.1.1 Cogmed. For individuals who completed Cogmed there was a significant difference in the visuospatial STM post-test subtest scores for individuals in the *average reading ability* group compared to those in the *reading difficulty* group, *t* (10) = -3.14, *p* = .010. However, no significant differences were found between the verbal STM, *t* (10) = .73, *p* = .482, verbal WM, *t* (10) = -1.88, *p* = .089, or visuospatial WM, *t* (10) = -1.99, *p* = .075, post-test scores of individuals in the *average ability* group compared to those in the *reading difficulty* group.

4.2.1.2 Control. For individuals in the *Control* group, no significant differences were found between any of the AWMA post-test scores of individuals in the *average ability* group compared to those in the *reading difficulty* group; verbal STM, *t* (11) = -.661, *p* = .522, visuospatial STM, *t* (11) = -.723, *p* = .485, verbal WM, *t* (11) = -.206, *p* = .840, and visuospatial WM, *t* (11) = -.192, *p* = .851.

4.2.2 Word reading. When reading ability was determined by scores on the WRAT 4 *word reading* subtest, some significant differences were found when an independent samples t-test was run. Descriptive statistics of post-test WM scores for individuals in the *Cogmed* and *Control* groups, with and without reading difficulties, when reading ability is split by *word reading* standard scores were calculated in order to provide a summary of the data for each group (see Table 6).

4.2.2.1 Cogmed. For the *Cogmed* group, a significant difference was found between the post-test visuospatial WM subtest scores of individuals in the *average reading* group compared to the *reading difficulty* group, *t* (10) = -2.770, *p* = .020. However, no significant differences were found between the *average ability* group and the *reading difficulty* group on post-test verbal STM, *t* (10) = 1.080, *p* = .305, visuospatial STM, *t* (10) = -1.952, *p* = .080, and verbal WM, *t* (10) = -.864, *p* = .408, subtest scores.

4.2.2.2 Control. For the *Control* group no significant differences were found between the *average ability group* and the *reading difficulty* group on post-test subtest scores. Specifically, verbal STM, *t* (9) = -.82, *p* = .453, visuospatial STM, *t* (9) = .74, *p* = .479, verbal WM, *t* (9) = -1.12, *p* = .293, and visuospatial WM, *t* (9) = -.43, *p* = .677.

Table 5

Summary of Mean and Standard Deviation (SD) for Post-Test WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Reading Composite Standard Scores) of Individuals in the Cogmed and Control Groups

	Cogmed				Control			
	Average Reading [a]		Reading Difficulty [b]		Average Reading [c]		Reading Difficulty [d]	
WM Component	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal STM	104.00	14.86	112.33	11.67	96.80	4.38	92.00	15.61
Visuospatial STM	121.67	17.93	99.67	21.00	106.40	5.46	102.13	12.32
Verbal WM	102.67	18.62	94.50	13.77	89.20	15.06	87.88	8.36
Visuospatial WM	120.00	16.40	97.50	11.27	98.60	23.58	96.88	8.44

Note. [a] *n* = 6, [b] *n* = 6, [c] *n* = 5, [d] *n* = 8

Table 6

Summary of Mean and Standard Deviation (SD) for Post-Test WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Word Reading Standard Scores) of Individuals in the Cogmed and Control Groups

	Cogmed				Control			
	Average Reading [a]		Reading Difficulty [b]		Average Reading [c]		Reading Difficulty [d]	
WM Component	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal STM	104.00	14.86	112.33	11.67	96.17	6.77	89.40	19.05
Visuospatial STM	121.67	17.93	99.67	21.00	107.67	7.58	104.80	4.55
Verbal WM	102.67	18.62	94.50	13.77	93.00	11.83	86.20	7.23
Visuospatial WM	120.00	16.40	97.50	11.27	101.83	16.24	98.20	10.33

Note. [a] *n* = 6, [b] *n* = 6, [c] *n* = 5, [d] *n* = 6

4.2.3 Sentence comprehension. When reading ability was determined by scores on the WRAT 4 *sentence comprehension* subtest, some significant differences were found when an independent samples t-test was run. Descriptive statistics of post-test WM scores for individuals in the *Cogmed* and *Control* groups, with and without reading difficulties, when reading ability is split by *sentence comprehension* standard scores were calculated in order to provide a summary of the data for each group (see Table 7).

4.2.3.1 Cogmed. For the *Cogmed* group, significant differences were found between the *average ability* group and the *reading difficulty* group on the post-test scores of the visuospatial STM, *t* (11) = -3.420, *p* = .006, verbal WM, *t* (11) = -2.155, *p* = .054, and visuospatial WM,

Table 7

Summary of Mean and Standard Deviation (SD) for Post-Test WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Sentence Comprehension Standard Scores) of Individuals in the Cogmed and Control Groups

	Cogmed				Control			
	Average Reading [a]		Reading Difficulty [b]		Average Reading [c]		Reading Difficulty [d]	
WM Component	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal STM	109.50	17.03	111.60	12.90	98.00	8.32	95.20	7.82
Visuospatial STM	123.50	15.61	93.20	15.42	106.00	5.18	100.20	15.24
Verbal WM	108.63	19.44	89.20	5.12	86.00	11.33	92.60	12.20
Visuospatial WM	117.88	16.89	98.00	12.53	97.17	19.97	92.60	7.09

Note. [a] $n = 8$, [b] $n = 5$, [c] $n = 6$, [d] $n = 5$

t (11) = -2.257, p = .045, subtests. However, no significant differences were found on the post-test verbal STM subtest scores of the *average ability* group compared to the *reading difficulty* group, t (11) = .235, p = .818.

4.2.3.2 Control. For the *Control* group no significant differences were found between the *average ability group* and the *reading difficulty* group on post-test subtest scores; verbal STM, t (9) = -.571, p = .582, visuospatial STM, t (9) = -.881, p = .401, verbal WM, t (9) = .930, p = .377, and visuospatial WM, t (9) = -.483, p = .641.

4.2.4 Differential effects of working memory training. Further analyses were performed in order to determine whether or not WM training had a differential effect on individuals with average reading ability compared to individuals with reading difficulties. A paired samples *t*-test was used to compare the pre-test and post-test WM subtest scores of individuals with average reading ability to those of individuals with reading difficulties who were in either the *Cogmed* group or the *Control* group. Reading ability was determined by standard scores on the WRAT 4 *sentence comprehension* subtest, since most of the significant differences reported earlier were found using this split. Descriptive statistics of pre- and post-test WM scores for individuals in the *Cogmed* and *Control* groups, with and without reading difficulties, when reading ability was split by sentence comprehension standard scores were calculated in order to provide a summary of the data for each group (see Table 8).

4.2.4.1 Reading difficulty. A marginally significant difference was found between the pre- and post-test verbal STM scores of individuals with *reading difficulty* who were in the *Cogmed* group, t (4) = -2.707, p = .054. Individuals with reading difficulties scored better on the

Table 8

Summary of Pre-test and Post-test Mean and Standard Deviation (SD) for WM Measures for Average Reading Ability and Reading Difficulty Groups (Based on Sentence Comprehension Standard Scores) of Individuals in the Cogmed and Control Groups

	Cogmed				Control			
	Average Reading [a]		Reading Difficulty [b]		Average Reading [c]		Reading Difficulty [d]	
WM Component	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal STM								
Pre-test	98.25	10.66	92.20	9.04	95.83	14.36	92.00	8.97
Post-test	109.50	17.03	111.60	12.90	98.00	8.32	95.20	7.82
Visuospatial STM								
Pre-test	115.75	19.96	90.60	17.24	98.67	10.33	98.00	16.14
Post-test	123.50	15.61	93.20	15.42	106.00	5.18	100.20	15.24
Verbal WM								
Pre-test	107.63	10.49	83.40	4.56	97.17	15.23	85.40	9.71
Post-test	108.63	19.44	89.20	5.12	86.00	11.33	92.60	12.20
Visuospatial WM								
Pre-test	112.75	21.47	83.20	10.94	104.17	20.12	93.00	10.22
Post-test	117.88	16.89	98.00	12.53	97.17	19.97	92.60	7.09

Note. [a] $n = 8$, [b] $n = 5$, [c] $n = 6$, [d] $n = 5$

verbal STM subtest after completing *Cogmed* training. No additional significant differences were found between the pre- and post-test scores of individuals in the *reading difficulty* group who were in the *Cogmed* group (visuospatial STM, t (4) = -.458, p = .671, verbal WM, t (4) = -1.619, p = .181, and visuospatial WM, t (4) = -2.579, p = .061).

No significant differences were found between the pre- and post-test subtest scores of individuals in the *reading difficulty* group who were in the *Control* group (verbal STM, t (4) = -.636, p = .560, visuospatial STM, t (4) = -.251, p = .814, verbal WM, t (4) = -.863, p = .437, and visuospatial WM, t (4) = .103, p = .923).

4.2.4.2 Average reading ability. No significant differences were found between the pre- and post-test subtest scores of individuals in the *average reading* group who were in the *Cogmed* group (verbal STM, t (7) = -1.471, p = .185, visuospatial STM, t (7) = -.850, p = .423, verbal WM, t (7) = -.161, p = .876, and visuospatial WM, t (7) = -.533, p = .611).

No significant differences were found between the pre- and post-test subtest scores of individuals in the *average reading* group who were in the *Control* group (verbal STM, *t* (5) = -.434, *p* = .682, visuospatial STM, *t* (5) = -1.263, *p* = .262, verbal WM, *t* (5) = 1.518, *p* = .189, and visuospatial WM, *t* (5) = .656, *p* = .541).

The implications of these findings are discussed in chapter 5.

Chapter 5: Discussion

The purpose of this study was to explore the working memory (WM) profiles of children with and without reading difficulties in order to determine whether or not their WM profiles differed. The study also explored whether or not computer-based WM training had differential effects on individuals with and without reading difficulties.

5.1 Relationship between Working Memory and Reading Difficulties

In terms of the studies first purpose, the results showed that there were some significant differences in the WM profiles of individuals with average reading ability compared to individuals with reading difficulty.

As discussed earlier, reading ability was determined using all three measures of reading ability on the WRAT 4 (Wilkinson & Robertson, 2006a) to explore whether or not the method of defining reading ability would affect the results (i.e., using single subtest versus composite scores). Initially, when reading ability was determined by an individual's score on the reading composite, which is a combination of the WRAT 4 (Wilkinson & Robertson, 2006a) word reading and sentence comprehension subtest scores, it was found that individuals with reading difficulty scored lower than individuals with average reading ability on the verbal WM measure. However, no differences were found between the scores of individuals with and without reading difficulties on any of the other WM measures (i.e., verbal STM, visuospatial STM, and visuospatial WM). This may be because there were no differences between the WM measures of individuals with and without reading difficulties or because the differences were not detected (i.e., possibly due to small sample size).

When the reading ability was determined by an individual's WRAT 4 word reading or sentence comprehension score separately, significant results were noted when reading ability was determined by sentence comprehension scores but not when reading ability was determined by word reading scores. Specifically, when reading ability was determined by reading comprehension ability, individuals with reading difficulties scored lower on measures of verbal STM, verbal WM, and visuospatial WM. However, when reading ability was determined by reading decoding ability no differences were found between the scores of individuals with and without reading difficulties. In other words, individuals with reading comprehension difficulties scored poorer on measures of verbal STM, verbal WM, and visuospatial WM than individuals without reading comprehension difficulties, while individuals with reading decoding difficulties did not score differently than individuals without reading decoding difficulties. Again, this may be because there were no differences between the WM measures of individuals with and without reading decoding difficulties or because the differences were not detected (i.e., possibly due to small sample size). It is also possible that there are differences between individuals with poor decoding skills versus individuals with poor reading comprehension skills.

Previous research has also found that individuals with reading difficulty have performed poorer on tasks of verbal WM than individuals without reading difficulty (e.g., Booth et al., 2014; Compton et al., 2012; DeJong, 1998; Nevo & Breznitz, 2013; Swanson & Jerman, 2007), which supports the results of this study. Furthermore, previous research has also found that individuals with reading difficulty have performed poorer on tasks of verbal STM than individuals without reading difficulty (e.g., Cohen-Mimran & Sapir, 2007; Pham & Hasson, 2014; Wang & Gathercole, 2013).

Furthermore, in the current study the significant differences between WM scores of individuals with and without reading difficulties were dependent on the reading ability measure used to split reading ability groups. Specifically, differences were noted in verbal STM, verbal WM, and visuospatial WM when individuals were split with regard to reading comprehension difficulties but no WM differences were noted when individuals were split with regard to reading decoding difficulties. Since differences were noted between the results of individuals with reading decoding difficulties and individuals with reading comprehension difficulties it is possible that using a composite reading score that assesses both abilities may be misleading. This may be due to the possibility that the WM profiles of individuals with reading decoding difficulties may be different from the WM profiles of individuals with reading comprehension difficulties.

5.2 Effect of Working Memory Training on Individuals With and Without Reading Difficulty

When WM was measured after WM training it was found that both verbal STM and verbal WM scores were higher in individuals who completed Cogmed WM training compared to individuals who did not complete training. This finding is supported by past research (e.g., Holmes et al., 2010). When the WM profiles of individuals with and without reading difficulties were compared, further differences were noted. After WM training, there was a difference between the visuospatial STM scores of individuals with and without reading difficulties, when reading ability was determined by the combination of a decoding and comprehension task. Furthermore, after WM training a difference was noted between the visuospatial WM scores of individuals with and without word decoding difficulties. When the WM scores of individuals with and without reading comprehension difficulties were compared after WM training, differences were noted in the scores of visuospatial STM, verbal WM, and visuospatial WM. Thus, WM training has differential effects on individuals with reading difficulties compared to those without reading difficulties. This is important to consider because despite WM training, there were still some differences between individuals with and without reading difficulties. Furthermore, it is possible that WM training affects individuals of varying reading ability differently.

No significant differences were found between individuals with and without reading difficulties who did not participate in WM training. This finding is interesting since the post-test WM scores of individuals in the control condition should have been comparable to the pre-test WM scores of the entire sample in which there were some significant differences between individuals with and without reading difficulties. Thus, it is possible that cell sizes for the t-tests run on the post-test scores, which were between five and eight individuals per cell, were too small to detect any real differences. The significant results that were noted could have been influenced by the large variability between some of the scores.

When pre and post test scores were compared, it was noted that the verbal STM scores of individuals with reading comprehension difficulties improved marginally more than the scores of individuals without reading comprehension difficulties. Specifically, while there was no increase in the pre versus post-test verbal STM scores in individuals without reading difficulty that completed Cogmed training, there was a marginal increase in verbal STM scores in individuals with reading difficulties who completed Cogmed training. Thus, while training helped to improve the verbal STM of individuals with reading difficulty, no similar gain was noted for individuals without reading difficulty. It is possible that individuals with reading difficulty had more room to grow than individuals without reading difficulties. It is also possible that individuals with reading difficulties responded better to the WM training tasks. This finding can inform individuals of the potentials of WM training for individuals with reading difficulties.

However, this result should be interpreted with caution given the small sample size and resultant chance of Type I error.

5.3 Limitations

Although some of the findings are interesting, there are several limitations that should be considered when interpreting the results of this study. First, the sample size for the reading ability groups were small which made it difficult to detect differences between groups. Since cell sizes were unequal when comparing the pre and post test results of individuals with and without reading difficulties a t-test was run rather than an ANOVA. The use of a t-test resulted in less statistical power and an increased risk of making a Type I error (Field, 2013). Increasing the risk of making a Type I error would mean that there were more chances that a statistical significance was reported (e.g., that the verbal WM of individuals with and without reading difficulties is different) when in fact there was no significant difference. Future studies should increase sample size so that statistical power can be increased and the chance of a Type I error can be reduced. Furthermore, future studies should consider using a Bonferroni correction, which divides the alpha level based on the number of *t*-tests run, in order to control for Type I error (Field, 2013).

Another concern with this study is the lack of normal distribution and the large variance between the scores (Field, 2013). There was a large variance in the data, therefore the sample may not have been representative of the population. Furthermore, outlying data may have added weight to the numbers farther from the mean and may have skewed the results. Moreover, because of the large variance between the scores, there was a greater risk of a Type I error and thus a greater chance that significant differences were found when there was none.

Furthermore, by using a median split to create reading ability groups, it is possible that our effect sizes were smaller, and our loss of power was greater, than if we would have compared them as continuous variables (Field, 2013). To explain, reading ability is a continuous variable, and splitting it into two groups may not have accurately reflected individuals with average reading ability and individuals with reading difficulty. For example, individuals who scored just above the mean were considered the same as individuals who scored at the top of the scale, and yet different from individuals who may have scored just below them. Increasing sample size would mean the data could be split into four rather than two groups allowing extremely good readers to be compared to extremely poor readers rather than comparing average readers to each other. This may have better reflected the differences between the WM profiles of good readers and poor readers and produced a greater likelihood of finding significant results.

5.4 Implications for Practice

Although caution should be exerted given the limited statistically significant results and the relatively small sample size, the results of the current study has several implications for practice.

For psychologists, this study reiterates the importance of keeping up to date with memory research and incorporating any new findings into practice. It also exemplifies that assessing memory should not be overlooked when working with individuals with reading difficulties. That is, working memory deficits may have an impact on individuals with learning difficulties, and therefore should not be disregarded. For example, individuals with WM deficits and learning difficulties have problems with tasks that require: both storage and retrieval of information (i.e., learning math facts, reading sight words), remembering and following multi-step instructions, and tracking their progress in activities (Gathercole & Alloway, 2008). An emphasis should also be placed on recommending strategies to improve WM if individuals are found to have WM deficits and reading difficulties. This is important since strategy training techniques and WM training are shown to boost academic performance (e.g., Holmes, Gathercole & Dunning, 2009; Klingberg, 2010). Furthermore, individuals with learning difficulties or WM deficits are less likely to develop and use strategies on their own (Dehn, 2008).

Given the current research findings, and the results of other similar studies, psychologists should work to provide information to parents, classroom teachers, special education teachers, and school administrators on the relationship between reading difficulties and WM deficits and on the current research concerning interventions. Furthermore, in the future, when the impact of WM training becomes clearer, the role of psychologists and researchers could be to advocate for individuals with memory difficulties by stressing the importance of WM training programs and encouraging school administrators to fund memory interventions. Providing support to individuals with WM deficits would make the learning process more effective for them. For example, early intervention opportunities could be maximized for a student with WM deficits since his or her basic skills (i.e., reading decoding) may be negatively impacted by these deficits which could affect the student's overall achievement (Gathercole & Alloway, 2008).

For educators, this study and others like it illustrate the potential impact that WM could have on students with reading difficulties. Teachers can use this information to understand the WM deficits that students with reading difficulties may have and can limit tasks that place an excessive load on WM when possible. For example, when requiring students with WM and reading difficulties to solve word based math problems teachers can keep vocabulary simple, increase the meaningfulness and familiarity of the material, and require students to practice similar types of problems until automaticity is attained (Gathercole & Alloway, 2008). Special education teachers could also use this information to inform their decisions on how to assist students with WM deficits and reading difficulties. School administrators should consider this information when determining the feasibility of implementing WM interventions (e.g., computer-based interventions) in schools.

5.5 Implications for Future Research

The results of this study also have implications for future research. Several significant results were found, which has improved our understanding of the relationship between WM and reading difficulties. Specifically, differences were found between individuals with and without reading difficulties in terms of WM profiles, and WM training appears to effect WM components differently, dependent on reading ability. These initial findings may prove beneficial when determining what types of WM training tasks are most effective for individuals with specific deficits. The significant results that were found indicate that there is value in continuing to explore the relationship between WM and reading ability. Future research should also consider reading difficulties when assessing the effect of WM interventions, since WM training may affect individuals with and without reading difficulties differently.

Even though many of the results of the current study were non-significant, looking at the descriptive statistics highlighted many interesting things. For example, when looking at the descriptive statistics for the post-test WM measures for individuals with and without reading difficulties who were in the Cogmed or Control group, some interesting trends are noted (see Table 5). Specifically, average readers had higher visuospatial STM, verbal WM, and visuospatial WM post-test scores after completing Cogmed than individuals with reading difficulty. Although, individuals with reading difficulty had higher post-test verbal STM scores after completing Cogmed than individuals with average reading ability. However, the only significant differences found were that the post-test visuospatial STM scores of average readers were different than those of individuals with reading difficulties. Although the results were not all significant they are still important to consider. For example, if related studies showed similar results the information from all of the non-significant research would provide more information regarding whether there was a lack of power to distinguish any differences between the WM profiles of individuals with and without reading difficulties or whether there simply were no differences.

Furthermore, considering non-significant results is important to future researchers in order to influence the formulation of research questions and to provide valuable information regarding what measures could be used. Future researchers can learn from the design of the current study and can determine more effective ways to answer similar questions. For example, splitting reading ability groups in different ways or measuring WM ability differently may have been more effective. Thus, even though many of the findings in the current study were non-significant, they can still provide valuable insight into WM and reading difficulties and should therefore be considered in future research.

Although the results from the small local sample used in this study are not generalizable to all students, they are useful as a starting point to consider how WM affects students with reading difficulties. Future studies, with increased sample sizes, would be beneficial in order to determine if similar, albeit significant, results could be replicated. Some additional directions for future research include: comparing different WM training programs for effectiveness, exploring if reading ability changes after WM training, investigating the long-term effects of WM training on the reading skills and WM profiles of individuals with and without reading difficulties, and exploring the effects of early WM training intervention on the early reading skills and WM profiles of young children with reading difficulties.

5.6 Conclusion

The current study explored the relationship between WM and reading difficulties. Although many of the results in this study did not reach statistical significance, a lot of important information can be gleaned. This information identifies that there are some differences between the WM profiles of individuals with and without reading difficulties, and that there are still differences after WM training.

Furthermore, my knowledge in the area of WM and WM training has grown substantially. I have learned to be a critical thinker when reading articles in this subject area.

Any conclusions made about a topic should be based on the results of numerous studies, rather than a single article. As a future psychologist, I have learned the importance of assessing WM thoroughly, especially when reading difficulties are involved. I have also learned the importance of offering recommendations to my clients that match their current areas of need and that are based on scientific evidence. In summary, this study has been a significant learning experience and the knowledge I have gained will assist me throughout my career.

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