EXPLORING THE RELATIONSHIPS BETWEEN CHILDREN'S WORKING MEMORY
AND LONG-TERM MEMORY

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By

Rachelle Lynn Jeworski

ABSTRACT

Working memory and long-term memory are two types of memory associated with children's learning and academic performance. A number of memory models have suggested there is a relationship between working memory and long-term memory; however, there is a lack of empirical research measuring this relationship using standardized assessment tools. Further, there are currently no studies measuring this relationship in children. The purpose of this study was to investigate the relationship between children's working memory (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory, using standardized assessment tools. The Automated Working Memory Assessment was used to measure working memory and the Woodcock-Johnson Tests of Cognitive Abilities – Third Edition was used to measure long-term memory. This study utilized secondary data from a larger SSHRC funded study. Participants included 41 children between grades 1 and 8. The majority of parents who volunteered to have their children participate identified them as having a disability (e.g., speech/language difficulty; learning disability). Kendall's tau-b revealed statistically significant correlations between four areas of working memory (i.e., verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and central executive) and long-term memory. Mann-Whitney tests revealed children with higher working memory abilities differed significantly from children with lower working memory abilities on measures of long-term memory. The findings from this study may have implications for both theory and practice. The relationship observed between working memory and long-term memory appears to align with widely accepted memory models (e.g., Baddeley, 2000; Dehn, 2008). The findings also suggest interventions designed to improve children's working memory may have the potential to enhance long-term memory abilities.

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Chapter 1: Introduction

Researchers and scholars have long been interested in the scientific study of memory (e.g., James, 1890), as well as individual differences in memory abilities (e.g., Jacobs, 1887). This interest is warranted, since memory problems are frequently associated with children's learning difficulties (e.g., language impairment, specific learning disorders, attention problems; Gathercole & Alloway, 2007) and academic performance (Alloway, Banner, & Smith, 2010). In the field of education, it is important for educators and professionals (e.g., psychologists) to understand the relationships among different types of memory (i.e., short-term memory, working memory, long-term memory) in order to effectively support children's academic learning and development.

Working memory is one type of memory receiving attention for its relationship with academic learning (Dehn, 2008). Working memory refers to the ability to store and manipulate information for brief periods of time (Baddeley & Hitch, 1974). A number of studies have suggested working memory underlies individual differences in learning (Gathercole, Lamont, & Alloway, 2008; Swanson & Siegal, 2001). For example, strong relationships between measures of working memory and areas of academic achievement such as reading, language, spelling, vocabulary development, reasoning, complex learning, and mathematics are well-documented (e.g., Berninger & Richards, 2002; Murray, 2010; Schuchardt, Maehler, & Hasselhorn, 2008; St Clair-Thompson & Gathercole, 2006; St Clair-Thompson et al., 2010; Swanson, Howard, & Saez, 2006).

Long-term memory is another type of memory associated with academic learning (e.g., Imbo & Vandierendonck, 2007; Swanson & Saschse-Lee, 2001). Long-term memory, also referred to as long-term storage and retrieval, refers to the ability to store and integrate new information in long-term memory and later fluently retrieve the stored information (e.g., names, items, ideas) through association (McGrew, 2009). Research suggests long-term memory plays a critical role in academic learning, especially in areas of reading and mathematics (e.g., Dehn, 2008; Imbo & Vandierendonck, 2007; Swanson & Saschse-Lee, 2001). For example, in order to solve arithmetic problems quickly, children draw from knowledge stored in long-term memory (Imbo & Vandierendonck, 2007).

Both working memory and long-term memory play important roles in children's academic development; however, there has been no prior research that has investigated the

relationship between these two types of memory in children, using standardized assessment tools (e.g., Automated Working Memory Assessment; Alloway, 2007; Woodcock-Johnson III Tests of Cognitive Abilities; Woodcock, McGrew, & Mather, 2001). Standardized assessments generate objective data that allows for comparisons to be made across tests using standard scores. These scores can be used to investigate the strength and direction of the relationship between different types of memory (Sattler, 2008). Further, standardized assessments allow for accurate comparisons between subgroups (e.g., age, gender). This information would be useful for developing programs (e.g., teaching memory strategies) and services (e.g., computerized memory training) directed at improving memory abilities in these subgroups.

Altmeyer and colleagues (2013) recently found both short-term memory (i.e., temporary storage of information) and working memory performances could predict performance on a long-term memory task. This study, which utilized a large sample of university students, represents one of the few studies focusing on the relationship between working memory and long-term memory, using standardized assessment tools. There are currently no available studies explicitly investigating this relationship in children. This is a critical area of research, as information may be used to guide intervention strategies (e.g., computerized memory training programs) for children struggling with academic performance. Children may have a variety of unique learning needs (e.g., visual learners) and cognitive deficits (e.g., memory impairment). Therefore, it is important to investigate the relationships between different types of children's memory in order to ensure evidence-based interventions are being used that best meet the needs of a variety of children (e.g., St Clair-Thompson et al., 2010). In addition, many schools have limited budgets; therefore, implementing expensive interventions and services must be done after careful consideration of relevant literature (e.g., Gibson et al., 2012).

Recently, a study looking at the effect of working memory interventions on various aspects of children's cognitive and academic performance has been conducted (Marche, McIntyre, & Claypool, 2015). Two of the areas of cognitive functioning being investigated are children's working memory and long-term memory. Specifically, the study is looking at whether working memory interventions (i.e., computerized working memory interventions and/or working memory strategy training) have the potential to improve children's long-term memory. Quantitative information on how children's working memory and long-term memory are related may contribute to the understanding of the effectiveness of working memory interventions on

children's long-term memory. These findings would have implications for educators and professionals working with children (i.e., school administrators, classroom teachers, special education teachers, psychologists, etc.) who are selecting and implementing evidence-based interventions in the school environment.

The relationship between working memory and long-term memory is often expressed qualitatively through the use of memory models. In Baddeley's (2000) model, a subsystem known as the episodic buffer integrates representations from components of working memory and long-term memory into unitary representations. Further, according to the Integrated Model of Working Memory (Dehn, 2008), working memory and long-term memory are very interactive. Long-term memory is used to recall and enhance working memory representations, making responses more automatic and less effortful. Working memory operates on memory representations, modifying long-term memory structures as new information is added (Dehn, 2010). Although these models suggest a relationship between working memory and long-term memory, there is limited research looking at this relationship from a quantitative perspective and a lack of information on how these types of memory relate in practice (e.g., Altmeyer et al., 2013; Swanson & Sachse-Lee, 2001). As such, these are areas of research in need of further exploration.

Statement of the Purpose

The purpose of the current research was to provide clarity on the nature of the relationship between children's working memory and long-term memory. This project conducted secondary data analyses using data extracted from a larger Social Sciences and Humanities Research Council (SSHRC) funded study looking at the effect of working memory interventions on various aspects of children's cognitive and academic performance (Marche et al., 2015). The results of these analyses will improve our understanding of the relationships between children's working memory and long-term memory, which has the potential to guide cognitive-based intervention strategies and support students with academic difficulties in the school environment. There is little quantitative information available on the relationship between working memory and long-term memory; therefore, results from this study may be helpful in understanding the effectiveness of working memory interventions on children's long-term memory.

Research Questions

The following research questions were posed:

1. Are children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores significantly related, as measured by standardized assessment tools?

2. Do children with higher working memory scores differ significantly from children with lower working memory scores on measures of long-term memory?

   a. Do children with higher verbal working memory scores differ significantly from children with lower verbal working memory scores on measures of long-term memory?

   b. Do children with higher visual-spatial working memory scores differ significantly from children with lower visual-spatial working memory scores on measures of long-term memory?

Definitions

For the purpose of adding greater clarity to this study, the following terms are defined:

Short-term memory. *Short-term memory* refers to the simple, temporary storage of information (Baddeley, 2012). For example, when an individual remembers a phone number just long enough to dial it, the information is temporarily stored in short-term memory.

Verbal short-term memory. *Verbal short-term memory* stores material that can be expressed through spoken language, such as numbers words, and sentences (Alloway, 2007).

Visual-spatial short-term memory. *Visual-spatial short-term memory* can store images, pictures, and information about locations (Alloway, 2007).

Working memory. *Working memory* refers to the ability to store and manipulate information for brief periods of time (Baddeley & Hitch, 1974). It provides a mental workspace for many important activities, such as reading and writing (Gathercole, Alloway, Willis, & Adams, 2006). For example, when students are writing sentences, they have to hold the information in their mind while spelling the individual words (Gathercole & Alloway, 2007).

Verbal working memory. *Verbal working memory* refers to the simultaneous storage and processing of verbal information (Alloway et al., 2008).

Visual-spatial working memory. *Visual-spatial working memory* refers to the simultaneous storage and processing of visual and spatial information (Alloway et al., 2008).

Central Executive. The *central executive* is a component of working memory that is made

up of verbal and visual-spatial working memory (Alloway, 2007). It is responsible for the control of attention and processing, which is involved in a range of regulatory functions including the retrieval of information from long-term memory (Baddeley, 1996).

Long-term memory. *Long-term memory* (also referred to as long-term storage and retrieval) refers to the ability to store and integrate new information in long-term memory and later fluently retrieve the stored information (McGrew, 2009). For example, if a teacher asked students a question about a concept they had learned the day before, the students would have to retrieve the information from their long-term memory in order to answer the question.

Chapter Organization

A review of the literature, including information on working memory and long-term memory as they pertain to standardized assessment and children's academic learning is presented in Chapter 2. Chapter 3 reviews the research participants, procedures, measures, and data analyses. The study results are presented in Chapter 4. Finally, Chapter 5 discusses the results and implications for practice and future research.

Chapter 2: Literature Review

This chapter includes a critical review of the literature related to working memory and long-term memory as they pertain to children's academic learning. The review is divided into two major sections. The first section considers the structure of memory, including a number of memory models that have been proposed over the years, and how working memory and long-term memory are defined, related, and impact academic learning. The second section looks at standardized assessment of working memory and long-term memory in children.

Conceptualizing Memory

Models of memory. There is general agreement among researchers that memory shows a substructure (Altmeyer et al., 2013). A number of memory models have been proposed over the years (e.g., Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974). The Atkinson-Shiffrin model of memory (Atkinson, & Shiffrin, 1968), which emerged in the late 1960's, gained wide acceptance. The Atkinson and Shiffrin model divided memory into three major types of storage: several sensory stores that accept information from one sense modality; a short-term store that accepts information from the sensory stores; and a long-term store that exchanges information with the short-term store. As research in this area continued, the Atkinson-Shiffrin model was criticized for oversimplifying memory and for placing too much emphasis on structure while ignoring the processes of memory. With the development of working memory theories, the model faded away. Nevertheless, the three-part division of memory in this model provides a useful framework for interpreting memory performance (Dehn, 2008).

Baddeley's model of working memory (Baddeley, 2000; Baddeley & Hitch, 1974) has served as a particularly useful theoretical tool in studies of children's memory (e.g., Alloway, Gathercole, & Pickering, 2006; Schuchardt et al., 2008). The original model included three components of working memory: (a) the phonological loop; (b) the visual-spatial sketchpad; and (c) the central executive (Baddeley & Hitch, 1974). The phonological loop is a limited-capacity, speech-based store of verbal information. The visual-spatial sketchpad is responsible for remembering and processing visual and spatial information. The central executive is the most complex component of working memory. It is a supervisory system that controls the actions of the phonological loop and the visual-spatial sketchpad. It is also thought to be capable of attentional focus, storage, and decision-making. Baddeley (2000) later added another subsystem known as the episodic buffer, which is responsible for integrating information from a variety of

sources in the cognitive system, including both temporary and long-term memory systems. The detailed structure of the episodic buffer and standardized methods of assessing its capacity have yet to be identified (Gathercole et al., 2004). Support for this model has been obtained from studies related to children (e.g., Alloway, Gathercole, & Pickering, 2006; Alloway, Gathercole, Willis, & Adams, 2004), adults (Kane, et al., 2004), and neuropsychology (Jonides, Lacey, & Nee, 2005).

The Integrated Model of Working Memory (Dehn, 2008) proposed short-term memory, working memory, and long-term memory are all independent types of memory that are constantly interacting with one another. According to Dehn (2008), working memory consists of verbal, visual-spatial, and executive components. Analysis, manipulation, and transformation of verbal information take place in verbal working memory. Visual-spatial working memory works to combine visual-spatial material held in both short-term and long-term memory (Dehn, 2008). Executive working memory is involved in tasks such as coordinating the interaction of memory subsystems and inhibiting irrelevant information. It is also responsible for the deliberate search for information in long-term memory (Dehn, 2008). Under the integrated model, working memory is more closely linked with long-term memory than with short-term memory. Although working memory continues to work with short-term memory, more of its resources are devoted to long-term memory. The close connection between working memory and long-term memory may explain working memory's strong relationship with academic learning (Dehn, 2008). Although the aforementioned memory models suggest a relationship between working memory and long-term memory, there is limited research examining the nature of the relationship between these two types of memory using standardized assessment tools (e.g., Altmeyer et al., 2013). Further, there are no studies explicitly looking at the nature of this relationship in children, representing a major gap in the literature.

Working memory. The term working memory evolved from the earlier concept of short-term memory (Baddeley, 2012). The two terms are still occasionally used interchangeably, however, short-term memory refers to the simple temporary storage of information whereas working memory refers to the combination of storage and manipulation of information over brief periods of time (Baddeley, 2012). Working memory underlies numerous skills that are essential for children in the classroom, such as reading, writing, and following directions (Gathercole et al., 2006; Gill et al., 2003). The primary function is to facilitate and enhance the capacity of

storage and retrieval functions that are essential for learning and higher level processing of information (Dehn, 2008).

Relationships between working memory and academic learning. A number of studies have suggested working memory underlies individual differences in learning (Gathercole et al., 2006; Swanson & Siegal, 2001). Children with learning disabilities often demonstrate deficits in working memory (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002). Learning disability refers to a number of disorders, which may affect the acquisition, organization, retention, understanding, or use of verbal or non-verbal information. These disorders affect learning in individuals who otherwise demonstrate at least average abilities essential for thinking and/or reasoning (Learning Disabilities Association of Saskatchewan, 2014). Strong relationships between measures of working memory and areas of academic achievement such as reading, language, spelling, vocabulary development, reasoning, complex learning, and mathematics have been well-documented (e.g., Berninger & Richards, 2002; Murray, 2010; Schuchardt et al., 2008; St Clair-Thompson & Gathercole, 2006; St Clair-Thompson et al., 2010; Swanson et al., 2006).

Swanson and colleagues (2006) looked at whether different components of working memory underlie differences in reading disabilities. The performance of three less-skilled reading subgroups was compared: (a) children with reading disabilities in reading comprehension and word recognition; (b) children with comprehension deficits only; and (c) children with low verbal IQ, reading comprehension, and word recognition with that of a group of skilled readers on measures of working memory, short-term memory, and a number of other executive functions, including updating (i.e., monitoring and coding information for relevance to the task at hand and then revising the items held in working memory; Swanson et al., 2006). Skilled readers outperformed less-skilled readers on measures of working memory, short-term memory, and updating (Swanson et al., 2006). Short-term memory and updating contributed to significant variance in working memory beyond what was contributed by reading skill classification (Swanson et al, 2006). These findings suggest a variety of executive functions may account for differences in reading abilities, and point to the need for further research in this area.

In a related study, Schuchardt and colleagues (2008) examined working memory functioning in children with specific learning disorders. They found different components of working memory were responsible for different scholastic abilities (Schuchardt et al., 2008). For

example, dyslexia (i.e., impairment in reading skills) was related to deficits (i.e., significantly lower than normal functioning) in phonological and central executive functioning, while dyscalculia (i.e., impairment in arithmetic skills) was related to deficits in visual-spatial functioning (Schuchardt et al., 2008).

Research suggests working memory deficits associated with dyslexia extend into adulthood (Smith-Spark & Fisk, 2007). Contrary to related research (e.g., Schuchardt et al., 2008), Smith-Spark and Fisk (2007) did not find that dyslexia was limited to deficits in phonological and executive functioning. Rather, they observed an association between dyslexia and all three components of working memory (i.e., phonological, executive, and visual-spatial components; Smith-Spark & Fisk, 2007). The aforementioned studies represent a small selection of the research on working memory and academic learning. The literature demonstrates strong agreement that deficits in working memory are associated with poor academic performance; however, studies demonstrate less agreement in terms of which components of working memory contribute to differences in specific areas of academic achievement as well as which other types of memory may be involved. One type of memory that is noticeably absent from this literature is long-term memory. Given the relationships between working memory and long-term memory (e.g., Dehn, 2008), the lack of research that includes measures of long-term memory represents a major gap in this area of research. Measures of long-term memory would provide insight into its unique contribution to working memory and academic learning.

Long-term memory. Long-term memory is a complex storage system with several different types of storage dispersed throughout the brain (Dehn, 2008). Long-term storage and retrieval refers to the ability to store and integrate new information in long-term memory and later fluently retrieve the stored information (e.g., names, items, ideas) through association (McGrew, 2009). By rehearsing information and associating it with other information that is already stored in long-term memory, new knowledge can be added to the store, which seemingly possesses unlimited capacity (Altmeyer et al., 2013).

Long-term memory is divided into two major categories (a) semantic memory and (b) episodic memory (Dehn, 2008). Semantic memory contains all of the general knowledge that we have acquired over time. It is critical for academic learning, as it is responsible for memory of facts, concepts, and rules. Semantic memory is thought to be organized by categories, associations, and meaning. In other words, items in the same category are more closely

associated with one another than are unrelated items (Dehn, 2008). These patterns in which information is organized are referred to as schemas (Altmeyer et al., 2013; Dehn, 2008). In a learning situation, schemas can be used to drastically reduce the complexity of a problem (e.g., by using an already proven technique to solve a specific problem instead of viewing it as something new; Altmeyer et al., 2013). Conversely, episodic memory is primarily autobiographical and contextual (Dehn, 2008). When applied to academic learning, episodic memory is responsible for information that is associated with the specific time and place that the information was learned (Leahey & Harris, 1989). For example, remembering the capital city of Canada is semantic memory; remembering that you first learned this on a class trip to Ottawa is episodic memory. Working memory works with all different types of long-term memory, but when it comes to learning, working memory primarily operates on semantic memory structures (Dehn, 2008). Long-term memory can also be divided into explicit and implicit. Explicit memories include information that the individual is consciously aware of and can deliberately manipulate. In contrast, knowledge that the individual is not aware of is stored in implicit memory (Dehn, 2008).

Although long-term memory makes contributions to short-term memory performance, there are characteristics of long-term memory that distinguish it from short-term memory: (a) long-term representations change slowly after repeated exposures to the same information, whereas short-term memory can immediately represent new information, (b) long-term memory stores long-term, relatively stable representations of the world, whereas short-term memories are less distinct (Brown & Hulme, 1996; Dehn, 2008). When individuals are asked to recall information temporarily stored in short-term memory, they often draw on long-term memory to enhance phonological and semantic representations (Logie, 1996). This explains why most individuals are able to remember more words than nonwords (Gathercole & Martin, 1996).

Relationships between long-term memory and academic learning. Long-term memory plays an important role in academic learning, especially in the areas of reading and mathematics (Imbo & Vandierendonck, 2007; Swanson & Sachse-Lee, 2001). In reading decoding, short-term memory and working memory carry the initial burden. Once practiced, a reader's decoding becomes more automated and long-term memory becomes more prominent. In order to accomplish reading comprehension and learn from it, information must be integrated with existing long-term schemas. An individual with a higher level of semantic knowledge on a topic

will achieve higher levels of comprehension. For example, individuals often find it easier to remember familiar words than they do unfamiliar words (Hulme, Maughan, & Brown, 1991). Therefore, individuals who lack semantic knowledge in long-term memory will likely experience problems with reading comprehension.

Another study investigated working memory involvement in typically developing children's use of arithmetic strategies (Imbo & Vandierendonck, 2007). Participants solved arithmetic problems and were asked to choose which strategy they had used (retrieval, count, transform, or other). The retrieval strategy was presented as such: "You solve the problem by remembering or knowing the answer directly from memory." Results showed more frequent retrieval use and more efficient memory retrieval reduced the demand on working memory and improved arithmetic performance. Results also showed that as children grow older, they become more efficient in the execution of retrieval (Imbo & Vandierendonck, 2007).

Floyd, Evans, and McGrew (2003) explored the relationships between a number of cognitive abilities, including long-term memory, and mathematics achievement. They found long-term memory was important to early mathematics skill development and calculation. Interestingly, this relationship was only significant for children aged six to eight years; long-term memory appears to be less predictive of mathematics achievement beyond age nine. The authors concluded this might have to do with the varying task demands of earlier simple problems versus more complex problems children are required to solve, as they get older (Floyd et al., 2003).

The aforementioned research suggests long-term memory is important for academic learning; however, much of this information comes in the form of assumptions made within the context of working memory studies. There is a limited amount of research utilizing tools specifically designed to measure long-term memory in order to investigate the unique role it plays in academic learning.

Relationships between working memory and long-term memory. Over the years, a number of theories have suggested there is a relationship between working memory and long-term memory. In the initial working memory model by Baddeley and Hitch (1974), there was no clear link between working memory and long-term memory. In his more recent model, Baddeley (2000) included an additional component called the episodic buffer, which provides a temporary interface between the working memory and long-term memory. The episodic buffer is controlled

by the central executive and plays an important role in feeding information into and retrieving information from long-term memory (Baddeley, 2000).

Alloway and colleagues (2004) explored the relationship between verbal short-term and working memory and the episodic buffer with a sample of 633 British children between the ages of four and six. As this was the first study attempting to measure the episodic buffer in children, the researchers developed a method of assessment for the purpose of the study (Alloway et al., 2004). They measured the episodic buffer by assessing children's sentence repetition skills, as this skill integrates information from temporary memory subsystems with the products of semantic and syntactic analysis by the language processing system (Alloway et al., 2004). Verbal short-term memory was measured with a digit-recall task and verbal working memory was measured with a backwards digit-recall task, tapping verbal storage of information and verbal storage and processing of information, respectively (Alloway et al., 2004). Results from this study revealed statistically significant correlations between verbal short-term and verbal working memory and the episodic buffer (Alloway et al., 2004). Further, the results demonstrated verbal short-term memory, verbal working memory, and the episodic buffer are separable, yet related systems, providing further support for Baddeley's (2000) model. One area of memory that was not measured in this investigation was long-term memory, despite being acknowledged for its role in relation to working memory and the episodic buffer (Alloway et al., 2004).

Another theory linking working memory and long-term memory is cognitive load theory (Paas, Renkl, & Sweller, 2004). This model has served as the theoretical foundation in studies looking at the relationship between working memory and long-term memory in adults (e.g., Altmeyer, 2013). According to cognitive load theory, there is a reciprocal relationship between working memory and long-term memory. Cognitive load theory looks at the processes that take place when information shifts from working memory to long-term memory as well as how working memory uses long-term memory content to function more efficiently. Information must be processed by working memory in order to be stored permanently in long-term memory. Doing so creates a specific load depending on the amount and type of information. If the load does not exceed the capacity of working memory, schemas, which increase the availability and access-speed of information, can be formed. Conversely, when working memory processes information that already has a schema, the complexity of a situation may be drastically reduced, thus a much smaller load and improved performance of working memory (Paas et al., 2004).

A recent study was conducted in order to investigate whether performance on working memory tasks and short-term memory tasks could predict performance in a long-term memory task (Altmeyer et al., 2013). From a sample of 209 university students, results showed that both working memory and short-term memory contributed significantly to the prediction of long-term memory. A possible limitation of this study is the task used to measure long-term memory, namely, the Posner task. The Posner task directly measures the retrieval speed of long-term memory contents. While retrieval fluency is often included as part of long-term memory measures, the Posner task may be missing other key components of long-term memory, such as associative memory. Therefore, the generalizability of the results may be limited based on the use of this measure of long-term memory. Nevertheless, this study is important as it represents one of the few empirical studies explicitly focused on investigating the relationship between working memory and long-term memory. To the researcher's knowledge, there have not yet been any studies examining this issue in children.

Historically, it has been thought that short-term memory and long-term memory were quite separate because some patients with short-term memory deficits appeared to have intact long-term memory (Baddeley & Hitch, 1974); however, subsequent research has found that such patients may show impairments in certain areas of long-term memory. For example, a particular patient, PV, with a very specific deficit in phonological (i.e., verbal) short-term memory was studied (Baddeley, Papangno, & Valler, 1988). Her auditory digit span was only two items; however, she had fluent language production and comprehension. PV underwent a series of experiments in which her results were compared to matched controls. In one experiment, which tested her capacity to learn pairs of unrelated words (e.g., castle, table), she was in the normal range. In a second experiment, which required her to associate a familiar word with an unfamiliar word from another language, she was completely unable to perform this task. These results suggest short-term phonological storage is important for some types of new long-term learning (Baddeley et al., 1988).

Research has been conducted on the relationship between working memory and mathematical problem solving in children with learning disabilities (Swanson & Sachse-Lee, 2001). Children with learning disabilities were found to be inferior on measures of word-solution accuracy compared to children who were chronically age-matched. Most salient to the current research is the discovery the contribution of working memory to word-solution accuracy was

mediated by long-term memory processes associated with the knowledge of algorithms, demonstrating further support for the notion that working memory resources must draw on relevant knowledge from long-term memory. Additionally, some children experience difficulties developing long-term memory representations of number concepts. It has been suggested this may be caused by deficits in working memory (Geary, 1993). These findings suggest the need for further research on whether working memory interventions have the potential to improve long-term memory functioning.

A growing number of neuroimaging studies have highlighted the role of the prefrontal cortex in both working memory and long-term memory (e.g., Blumfeld & Ranganath, 2006; Ranganath, Johnson, & D'Esposito, 2003). Ranganath and colleagues (2003) investigated whether prefrontal regions activated during working memory tasks are distinct from regions activated during long-term memory tasks. Functional magnetic resonance imaging (fMRI) was used to identify patterns of activation associated with encoding and recognition during both working memory and long-term memory tasks. Results demonstrated that ventrolateral prefrontal regions and dorsolateral prefrontal regions of the brain were activated during both types of working memory and long-term memory tasks, supporting the notion that the same regions of the prefrontal cortex are engaged during working memory and long-term memory tasks (Ranganath et al., 2003).

Assessment of Memory in Children

Assessment is a method for understanding a child in order to make informed decisions about the child (Sattler, 2008). Psychological assessment information, including information on children's memory, can be gathered in a number of different ways, including standardized (i.e., norm-referenced) measures, interviews, behavioural observations, and informal assessment (Sattler, 2008). Standardized measures (i.e., Automated Working Memory Assessment; Alloway, 2007; Woodcock-Johnson III Tests of Cognitive Abilities; Woodcock, McGrew, & Mather, 2001) were the type of assessment used for the current study. These measures are standardized on a representative group (i.e., characteristics such as age, gender, ethnicity) who took the test. The test instructions, time limits, and scoring criteria are used in the same way by all examiners. The purpose of standardized assessment tools is to provide objective, quantitative scores, which can be used to describe the child's current level of functioning, to interpret the child's specific strengths and weaknesses, and to provide a baseline in order to measure progress over time

(Sattler, 2008). Further, these scores can be used in quantitative research in order to investigate statistical relationships between scores and examine group differences.

Assessment of working memory. There are a number of standardized measures that can be used to measure children's memory. Children's working memory can be assessed using measures such as the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003), which includes two subtests that provide a working memory index score, the Woodcock-Johnson Tests of Cognitive Abilities – Third Edition (Woodcock, McGrew, and Mather, 2001), which provides a short-term memory cluster score that includes measures of working memory, and the Automated Working Memory Assessment (Alloway, 2007), which measures verbal short-term memory, visual-spatial short-term memory, verbal working memory, and visual-spatial working memory separately.

Data from the Automated Working Memory Assessment (AWMA; Alloway, 2007) was used in the current study representing measures of short-term memory and working memory. The development of the AWMA was based on a multiple component working memory system (Baddeley & Hitch, 1974; Baddeley, 2000). It is a computerized measure that can be used by educational professionals to screen individuals aged four to 22 years for working memory problems. Alloway and colleagues (2006) looked at each of the memory components measured by the AWMA in a large sample of children aged four to 11 years in order to investigate the underlying structure of working memory. They found tasks on the AWMA aligned with Baddeley's working memory model (Baddeley & Hitch, 1974). They also found the underlying cognitive structure for working memory appears to be in place by four years of age (Alloway et al., 2006). Further, Alloway and colleagues (2008) found a high degree of convergence in performance between the AWMA and the WISC-IV working memory index (Wechsler, 2003). Notably, the WISC-IV utilizes a composite of forward and backward digit span tasks as a measure of working memory. In the AWMA, the forward digit span task is considered a measure of verbal short-term memory and the backward digit span task is considered a measure of verbal working memory. Alloway and colleagues (2008) suggest backward digit recall provides a stronger indicator of working memory skills than forward digit recall.

The AWMA has been used to assess children's working memory functioning in a number of empirical studies (e.g., Alloway, Gathercole, Kirkwood, and Elliot, 2009; Holmes et al., 2010). For example, Holmes and colleagues (2010) used the AWMA in order to provide pre and

post intervention scores for their study looking at the effectiveness of working memory training versus stimulant medication on working memory performance in children with ADHD. The AWMA was especially useful because it provided information on each of the four components measured by the AWMA, namely verbal short-term memory, visual-spatial short-term memory, verbal working memory, and visual-spatial working memory. One of the major limitations of the AWMA is that it does not provide an overall working memory score nor a measure of the central executive component of working memory. Rather, verbal working memory and visual-spatial working memory are only measured independently. This limitation appeared to be noticed by Holmes and colleagues (2010), as they made assumptions about participants' gains in central executive functioning, based on observations of their performances on the verbal and visual-spatial working memory tasks.

Assessment of long-term memory. Compared to working memory, there appear to be less standardized measures available to assess children's long-term memory. The WISC-IV (Wechsler, 2003) does not provide a long-term memory score; however, the Information subtest, which requires the child to answer questions about different topics, such as body parts, calendar information, historical information, and geographical facts, measures long-term memory for factual information (i.e., semantic long-term memory; Sattler, 2008).

The Woodcock-Johnson III (WJ-III; Woodcock, McGrew, & Mather, 2001a) consists of two distinct batteries, namely the WJ-III Tests of Cognitive Abilities (WJ-III COG; Woodcock, McGrew, & Mather, 2001c) and the WJ-III Tests of Achievement (WJ-III ACH; Woodcock, McGrew, & Mather, 2001b). Together, these batteries comprise a comprehensive system for measuring general intellectual ability, specific cognitive abilities, and academic achievement. The theoretical foundation of the WJ-III is derived from the Cattell-Horn Carroll theory of cognitive abilities (CHC theory). The utility of this theory for psychological assessment is in clarifying individual cognitive strengths and weaknesses that are best understood through the operationalization of broad and narrow abilities (Flanagan & Harrison, 2012).

The WJ-III COG (Woodcock et al., 2001c) provides a long-term storage and retrieval cluster, which consists of two subtests, namely Visual-Auditory Learning and Retrieval Fluency. This cluster, which measures the ability to retrieve previously stored information from long-term memory, was used as the measure of long-term memory in the current study. The Visual-Auditory Learning subtest measures associative memory and the Retrieval Fluency subtest

measures ideational fluency. According to CHC theory, the long-term storage and retrieval broad ability refers to the ability to store and integrate new information in long-term memory and later fluently retrieve the stored information (e.g., names, items, ideas) through association (McGrew, 2009). This ability can be measured in terms of information stored for minutes, hours, weeks, or longer (McGrew, 2009). According to Horn's model of intelligence (Horn & Blankson, 2005), long-term memory is also referred to as fluency of retrieval from long-term memory. In other words, when it comes to psychological assessment, the concepts of long-term memory and long-term storage and retrieval appear to be used interchangeably.

The WJ-III COG (Woodcock et al., 2001c), and more specifically, the long-term storage and retrieval cluster, has been used to assess children's long-term memory in a number of empirical studies (e.g., Rizza, McIntosh, & McCunn, 2001; Taub et al., 2008). For example, the WJ-III COG (Woodcock et al., 2001c) was used in a study assessing whether gifted and non-gifted students display similar patters of performance across CHC clusters (Rizza et al., 2001). As expected, the results of this study revealed gifted students performed significantly higher across tests than the non-gifted group. Further, results of the study demonstrated the WJ-III COG appears to be a good measure for assessing both high functioning and average functioning children (Rizza et al., 2001). The study did not include a sample of low functioning children in order to compare the pattern of performance across all levels of functioning, representing a potential area for future research.

Summary

A number of widely accepted memory models propose a relationship between working memory and long-term memory systems (e.g., Baddeley & Hitch, 1974; 2000; Dehn, 2008). Additionally, research suggests working memory and long-term memory abilities are important for children's academic learning (e.g., Imbo & Vandierendonck, 2007; Schuchardt et al., 2008). Currently, there are no studies using standardized assessment tools to investigate the nature of the relationship between children's working memory and long-term memory. This information is critical in order for educators and professionals in the field to make informed decisions regarding intervention strategies for children who are struggling with academic achievement. Chapter 3 will discuss the methods used to investigate the relationship between children's working memory and long-term memory, based on secondary data from a research study looking at the effect of

working memory interventions on various aspects of children's cognitive and academic performance (Marche et al., 2015).

Chapter 3: Method

This project utilized secondary data from a Social Sciences and Humanities Research Council of Canada (SSHRC) funded project looking at the effects of computer-based and strategy-based working memory interventions on cognitive abilities and academic performance in children (Marche et al., 2015). Approval from the University of Saskatchewan's Behavioural Research Ethics Board for the larger project, and graduate student use of data for secondary analyses, was received May 21, 2014 (BEH# 14-51). The current study examined the relationships between children's working memory and long-term memory by looking at scores from standardized measures of working memory (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory.

Research Questions and Hypotheses

The following research questions were posed:

1. Are children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores significantly related, as measured by standardized assessment tools?

2. Do children with higher working memory scores differ significantly from children with lower working memory scores on measures of long-term memory?

   a. Do children with higher verbal working memory scores differ significantly from children with lower verbal working memory scores on measures of long-term memory?

   b. Do children with higher visual-spatial working memory scores differ significantly from children with lower visual-spatial working memory scores on measures of long-term memory?

The first research question investigated whether children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores were significantly related, as measured by standardized assessment tools. Children's working memory and long-term memory scores were expected to be significantly related, based on findings of previous research studies and current models of working memory (e.g., Baddeley & Hitch, 1974,

2000; Dehn, 2008). Verbal short-term memory and long-term memory were expected to be highly related (i.e., $r \geq .80$; Sattler, 2008), based on research that has found verbal short-term memory is necessary for new long-term phonological learning (e.g., associating a familiar word with an unfamiliar word; Baddeley, Papagno, & Vallar, 1988). Further, the central executive and long-term memory were expected to be highly related (i.e., $r \geq .80$; Sattler, 2008) because the central executive system is responsible for higher-level thinking processes, such as problem solving, which requires retrieval of information from long-term memory stores (e.g., Imbo & Vandierendonck, 2007).

The second research question explored whether children with higher working memory scores differ from children with lower working memory scores on measures of long-term memory. Working memory and long-term processes are said to have reciprocal influences on one another (Dehn, 2008). In other words, working memory and long-term memory rely on one another in order to function effectively. Therefore, groups (i.e., higher and lower working memory) are expected to differ significantly on measures of long-term memory.

Participants

Data from 41 children between grades 1 and 8 who participated in a larger SSHRC funded project (Marche et al., 2015) were used to conduct secondary data analyses in this study. Most of the participants were recruited from two urban school divisions in Saskatchewan through advertisements that specified children with memory difficulties, reduced school performance, or attention disorders may benefit from the interventions/strategies offered in the study. Therefore, the majority of parents who volunteered to have their children participate identified them as having a disability (e.g., speech/language difficulty, learning disability). That is, formal diagnoses of language and/or learning difficulties or disabilities were not required to participate in this study.

Measures

The larger SSHRC funded study (Marche et al., 2015) utilized a number of standardized assessment measures to collect data, including the Automated Working Memory Assessment (Alloway, 2007), the Wechsler Intelligence Scales for Children – Fourth Edition (Wechsler, 2003), the Woodcock-Johnson Tests of Cognitive Abilities – Third Edition (Woodcock et al., 2001), the Wide Range Achievement Test – Fourth Edition (Wilkinson & Robertson, 2006), and the Peabody Picture Vocabulary Test – Fourth Edition (Dunn & Dunn, 2007). The current study

focused on secondary data obtained from two of these measures, namely the Automated Working Memory Assessment (Alloway, 2007) and the Woodcock-Johnson Tests of Cognitive Abilities – Third Edition (Woodcock et al., 2001).

Automated working memory assessment (AWMA). The AWMA (Alloway, 2007) is a standardized, computer-based screening tool that includes three measures each of the verbal and visual-spatial aspects of short-term memory and working memory for individuals aged 4 to 22. The AWMA (Alloway, 2007) is highly congruent with the WISC-IV Working Memory Index (Alloway, Gathercole, Kirkwood, & Elliot, 2008). Test-retest reliability ranges from .69 to .90 (Alloway, 2007). The AWMA (Alloway, 2007) is not heavily influenced by socio-economic factors (Alloway, 2007). Four subtests (i.e., one subtest in each of the four areas) from the AWMA (Alloway, 2007) were administered to participants in the larger study (Marche et al., 2015): (a) verbal short-term memory (Forward Digit Recall); (b) visual-spatial short-term memory (Dot Matrix); (c) verbal working memory (Backwards Digit Recall); and (d) visual-spatial working memory (Mr. X).

Woodcock-johnson tests of cognitive abilities – third edition (WJ-COG-III). The WJ-COG-III (Woodcock et al., 2001) is an individually administered, norm-referenced test designed to measure general and specific cognitive functions of individuals aged 2 to 90+. The WJ-COG-III (Woodcock et al., 2001) is comprised of a standard and an extended battery: The standard battery includes 10 subtests (e.g., Visual-Auditory Learning, Spatial Relations, and Concept Formation); the extended battery includes 10 additional subtests (e.g., Retrieval Fluency, Picture Recognition, and Decision Speed). The WJ-COG-III (Woodcock et al., 2001) demonstrates high internal consistency reliability (.80s to .90s), high test-retest reliability (.70s to .90s), and very high interrater reliability (upper .90s). The WJ-COG-III (Woodcock et al., 2001) also demonstrates evidence for internal validity, concurrent validity, and predictive validity (Cizek, 2006; Sandoval, 2006). The Visual-Auditory Learning and Retrieval Fluency subtests form a composite measure of long-term memory, which were administered to participants in the larger study (Marche et al., 2015).

Procedure

Once the initial psychological assessments for the larger SSHRC funded study (Marche et al., 2015) were completed, the current study gained access to the participants' files. Participant files were given numerical identifiers; therefore, no participant names were linked to the data.

Extracted secondary data from the participants' files included: (a) demographic information (i.e., gender, ethnicity, grade level, school, first language, disabilities and/or medical conditions, medications); and (b) psychological assessment information (i.e., measures employed, dates of assessments, standard scores). For the purposes of the current project, only data collected before March 2015 was used for statistical data analyses.

Statistical Data Analyses

Data were entered into statistical analysis software program, SPSS 22.0 for Windows (IBM Corporation, 2015). Descriptive statistics (i.e., mean, standard deviation, range) were computed for demographic variables (e.g., grade level, gender, ethnicity) in order to provide a characteristic summary of the participant sample and to provide insight into the generalizability of the statistical results. Preliminary analyses, with a focus on checking the assumptions of the secondary data, revealed violations of the assumptions associated with parametric data (e.g., normality, interval data). Therefore, non-parametric statistical tests were used to analyze the data for the current study.

Research question 1. The first research question posed was: What are the relationships between children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores, as measured by standardized assessment tools? Kendall's tau-b correlational procedure was used to measure the relationships between variables (i.e., verbal short-term memory, visual-spatial short-term memory, verbal working memory, visual-spatial working memory, the central executive, and long-term memory) using standard scores obtained from the AWMA (Alloway, 2007) and the WJ-COG-III (Woodcock et al., 2001).

The AWMA provides standard scores for four areas of working memory (verbal short-term memory, visual-spatial short-term memory, verbal working memory, and visual-spatial working memory). It does not, however, provide scores for the central executive component of working memory, which is made up of verbal working memory and visual-spatial working memory (Alloway, 2007). For the purposes of the current study, standard scores from the verbal working memory and visual-spatial working memory subtests were averaged together in order to generate an estimate of central executive functioning (see Holmes et al., 2010). The estimate of the central executive represents only a small aspect of this complex system.

Kendall's tau-b (τ) is a suitable non-parametric alternative that can be utilized with small sample sizes to yield a correlation coefficient much like a Pearson product-moment correlation coefficient (Field, 2009). Although Spearman's statistic is the more popular non-parametric alternative to Pearson correlation, Kendall's tau-b is more useful for data with a large number of tied ranks, generating a better estimate of the correlation in the population (Field, 2009).

Research question 2. The second research question asked: Do children with higher working memory scores differ from children with lower working memory scores on measures of long-term memory? The Mann-Whitney test, a non-parametric equivalent to the independent sample t-test, was used to determine if there was a significant difference in long-term memory scores for children with higher verbal working memory versus lower verbal working memory, as well as whether there was a significant difference in long-term memory scores for children with higher visual-spatial working memory versus lower visual-spatial working memory (Field, 2009; Glass & Hopkins, 1996).

The AWMA (Alloway, 2007) does not provide an overall measure of working memory. Therefore, verbal working memory scores and visual-spatial working memory scores were explored separately. The groups were separated based on standard scores on the verbal working memory subtest and the visual-spatial working memory subtest. The higher working memory groups had standard scores at or above the mean (i.e., equal to or greater than 100). The lower working memory groups had standard scores below the mean (i.e., less than 100). Knowledge of these group differences may provide additional insight into whether the relationships between working memory and long-term memory are affected by children's level (i.e., higher or lower) of working memory functioning. Further, these analyses explored if verbal working memory and visual-spatial working memory differ in how they are related to long-term memory based on children's level of working memory functioning in those areas.

Chapter 4: Results

Secondary data analyses were used in this study to examine the relationships between children's working memory and long-term memory by looking at scores from standardized measures of working memory (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory.

Participant Characteristics

Descriptive statistics were calculated for the collected data set, from 41 participants (23 males, 18 females) used for the study. Demographic information was extracted from participants' files via the demographic questionnaire, which was completed by the participants' parents. Participants' school grade level ranged from grade one to grade eight; however, the majority (82.9%) of participants were between grades three and seven. The majority (82.9%) of participants identified themselves as Caucasian. Alternatively, 7.3% identified themselves as Aboriginal/Metis/Inuit, 4.9% as Hispanic/Latino, 2.4% as Asian/Pacific Islander, and 2.4% as Other. Participants were also asked to disclose disabilities and/or medical conditions, which could be selected from a list of options on the demographics questionnaire. Please note, in relation to the number of participants identified as having each disability/medical condition, many of these disorders exist co-morbidly. The most common disabilities identified included speech/language difficulties, ADHD, learning disabilities, and anxiety (see Table 1). Notably, the demographics questionnaire did not specify whether the disabilities/medical conditions required a formal diagnosis made by a professional. Some parents appeared to select disabilities they suspected their child to have, rather than only disabilities diagnosed by a professional. As such, these results should be interpreted with this in mind. Further, since the majority of participants in this sample were identified as having a disability, this sample would not be considered an accurate representation of the general population.

Data Analyses

Preliminary analyses. Parametric data analyses require that certain assumptions be met in order for the results to be considered accurate. Therefore, preliminary analyses were conducted in order to explore the nature of the observed data. Most parametric tests based on the normal distribution have four basic assumptions: (1) normally distributed data; (2) homogeneity

Table 1

Participants with Disability/Medical Condition

Disability/Medical Condition	*n*
Attention-Deficit/Hyperactivity Disorder	7
Oppositional Defiant Disorder/Conduct Disorder	1
Learning Disability	7
Speech/Language Difficulties	12
Auditory Processing Disorder	2
Anxiety	6
Depression, Low Mood, or Dysphoria	2
Autism Spectrum Disorder	2
Acquired Brain Injury	0
Epilepsy	0
Diabetes	0
IQ Below 70	0
Vision Difficulties	1
Hearing Difficulties	1
Tics	0
Severe Allergies	1
Other	4

of variance; (3) interval data; and (4) independence. The assumption of normality was checked by inspecting skew and kurtosis values, histograms, and the Kolomgorov-Smirnov test. All but two variables, namely verbal short-term memory and long-term memory, demonstrated skew and kurtosis values very close to zero, suggesting the two named variables were not likely to be normally distributed (Field, 2009). Skew and kurtosis values were converted to z-scores in order to compare values in different samples that used different measures (Field, 2009). A z-score greater than 1.96 is significant at $p < .05$, greater than 2.58 is significant at $p < .01$, and greater than 3.29 is significant at $p < .001$. *Z*-score calculations revealed kurtosis z-scores of 2.64 for

verbal short-term memory and 4.17 for long-term memory, suggesting there was significant kurtosis for both of these variables.

Normality was further assessed through the use of the Kolmogorov-Smirnov test, which compared the observed distribution to a normal distribution (Field, 2009). According to the results from the Kolmogorov-Smirnov test, the only measured variable that demonstrated a distribution significantly different from a normal distribution was verbal working memory. Overall, the observed data appear to violate the assumption of normality. According to Sattler (2008), standardized tests scores that are designed to follow a normal distribution, such as the WJ-III COG, use ordinal measurement scales even though these tests scores are often said to use interval measurement scales. Based on this information, the observed data also violated the assumption of interval data. Given the violations of the assumptions associated with parametric data, non-parametric statistical analytic procedures were used for the current study. Specifically, Kendall's Tau was used in place of Pearson product-moment correlation and Mann-Whitney was used in place of independent samples t-test.

Research question 1. The first research question investigated: Are children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores significantly related, as measured by standardized assessment tools?

Kendall's tau-b generated a correlation matrix containing all of the variables, with a specific focus on the relationships between the working memory variables (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory. Results of this analysis indicated statistically significant positive relationships between four of the working memory variables (i.e., verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and the central executive) and long-term memory. Verbal short-term memory was the only variable that did not demonstrate a significant relationship with long-term memory. In other words, higher working memory scores were generally associated with higher long-term memory scores and lower working memory scores were generally associated with lower long-term memory scores. Overall, these results aligned with the hypothesis for this research question (i.e., working memory scores were expected to be significantly related to long-term memory scores); however, it was predicted verbal short-term memory and the central executive would be highly related

(i.e., $r \geq .80$; Sattler, 2008) related to long-term memory. Verbal short-term memory did not demonstrate a statistically significant relationship to long-term memory ($\tau = .214$, $n = 41$, $p = .053$). The central executive demonstrated a moderately low ($\tau = .396$, $n = 41$, $p = .000$) statistically significant relationship with long-term memory. Table 2 outlines the numerical significance of the relationships between the measured variables.

      Research question 2. The second research question investigated: Do children with higher working memory scores differ significantly from children with lower working memory scores on measures of long-term memory?

      The AWMA (Alloway, 2007) does not provide an overall measure of working memory. Rather, verbal working memory and visual-spatial working memory are measured independently. The groups were separated based on standard scores on the verbal working memory subtest and the visual-spatial working memory subtest. The higher working memory groups had standard scores at or above the mean (i.e., equal to or greater than 100). The lower working memory groups had standard scores below the mean (i.e., less than 100). For verbal working memory, the higher group had 17 participants and the lower group had 24 participants. For visual-spatial working memory, the higher group had 20 participants and the lower group had 21 participants. Despite having a sample of children with a number of identified disabilities, the groups were fairly well balanced around the mean; however, the lower working memory groups did have slightly more participants than the higher working memory groups.

      Two Mann-Whitney tests were used in order to examine group differences with respect to long-term memory. Results from the first Mann-Whitney test suggested groups (i.e., higher verbal working memory and lower verbal working memory) differed significantly on measures of long-term memory ($U = 126.00$, $z = -2.065$, $p = .039$, $r = 0.3$). Results from the second Mann-Whitney test suggested groups (i.e., higher visual-spatial working memory and lower visual-spatial working memory) also differed significantly on measures of long-term memory ($U = 15.5$, $z = -2.466$, $p = .014$, $r = 0.4$), which aligned with the hypothesis for this research question (i.e., groups were expected to differ significantly on measures of long-term memory). In order to further investigate the second research question, a number of additional correlations were completed. These analyses revealed correlations were not statistically significant between higher verbal working memory (i.e., greater than or equal to 100) scores and long-term memory scores ($\tau = .076$, $n = 17$, $p = .678$). Similarly, correlations were not statistically significant between

Table 2

Summary of Correlations Between Working Memory and Long-Term Memory Scores

Measure	V STM	VS STM	V WM	VS WM	CE	LTM
V STM	-	.029	.445**	.087	.322**	.214
VS STM	-	-	.220*	.479**	.458**	.354**
V WM	-	-	-	.266*	.629**	.248*
VS WM	-	-	-	-	.649**	.401**
CE	-	-	-	-	-	.396**
LTM	-	-	-	-	-	-

Note. V STM = Verbal Short-Term Memory; VS STM = Visual-Spatial Short-Term Memory; V WM = Verbal Working Memory; VS WM = Visual-Spatial Working Memory; CE = Central Executive; LTM = Long-Term Memory.
*p < .05. ** p < .01.

lower verbal working memory (i.e., less than 100) scores and long-term memory scores (τ = .124, *n* = 24, *p* = .409). In contrast, statistically significant correlations were found between higher visual-spatial working memory scores and long-term memory scores (τ = .409, *n* = 20, *p* = .013). Correlations were not statistically significant between lower visual-spatial scores and long-term memory scores (τ = .290, *n* = 21, *p* = .073). Although the initial correlations (see Table 2) suggested statistically significant relationships between long-term memory and all of the measured areas of working memory except verbal short-term memory, results from these correlations indicated the relationship between children's working memory and long-term may be affected by the child's level of working memory functioning. Notably, these correlations included a much smaller sample size than the initial correlations, which may have contributed to the lack of statistical significance. The implications of these findings are discussed in Chapter 5.

Chapter 5: Discussion

The purpose of the current study was to provide clarity on the nature of the relationship between children's working memory and long-term memory. Specifically, the purpose was to measure the relationship between children's working memory and long-term memory scores using standardized assessment tools. A number of memory models (e.g., Baddeley & Hitch, 1974; Dehn, 2008) suggest there is a relationship between working memory and long-term memory processes; however, there is little available research providing quantitative descriptions of this relationship using standardized assessment tools. Further, to the researcher's knowledge, there are no studies looking at these relationships in children, despite strong relationships found between memory functioning and academic learning and development (e.g., Imbo & Vandierendonck, 2007; St Clair-Thompson et al., 2010). A precise grasp of the relationship between children's working memory and long-term memory will add to our understanding of children's memory processes and may help guide educators and professionals working with children (i.e., school administrators, classroom teachers, special education teachers, psychologists, etc.) as to the best means of delivering instruction and interventions (e.g., strategy training, computerized memory training) to children with memory deficits.

Findings

Research question 1. The first research question posed: Are children's working memory scores (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory scores significantly related, as measured by standardized assessment tools?

It was predicted that children's working memory scores and long-term memory scores would be significantly related. Verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and central executive were found to be significantly related to long-term memory. Verbal short-term memory was the only variable that did not demonstrate a significant relationship to long-term memory. Overall, this finding aligned with Altmeyer and colleagues' (2013) research, which demonstrated significant relationships between working memory, short-term memory, and long-term memory using adult participants. This finding suggests the relationship between children's working memory and long-term memory may be similar for both children and adults.

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Further, it was predicted that both verbal short-term memory and the central executive would be highly related to long-term memory. In contrast to the predicted relationship, neither verbal short-term memory nor the central executive were highly related to long-term memory. Verbal short-term memory was not significantly related to long-term memory, while the central executive demonstrated a moderately low statistically significant relationship to long-term memory. In other words, although neither verbal short-term memory nor the central executive were found to be highly related to long-term memory, the central executive was much closer to reaching this level than verbal short-term memory.

The non-significant relationship found between verbal short-term memory and long-term memory is in contrast to research, which suggested verbal short-term memory is necessary for new long-term phonological learning (e.g., associating a familiar word with an unfamiliar word; Baddley, Papagno, & Vallar, 1988). The lack of statistical significance may have been due to the smaller sample size or due to the nature of the task used to measure long-term memory. The long-term memory composite on the WJ-III COG is comprised of a task that measures associate memory (i.e., Visual-Auditory Learning) and a task that measures ideational fluency (i.e., Retrieval Fluency). The Visual-Auditory Learning task likely taps long-term phonological learning more than the Retrieval Fluency task. Therefore, future research would benefit from looking specifically at the relationship between a task that measures verbal short-term memory and a task, such as Visual-Auditory Learning, that measures associative memory to see if these measures demonstrate a significant relationship and align with previous research (e.g., Baddeley et al., 1988).

Verbal short-term memory and verbal working memory were found to have the weakest relationships to long-term memory out of all of the measured variables, although the relationship between verbal working memory and long-term memory was found to be statistically significant. One reason for this finding may be that many (n=12) of the participants were reported to have speech/language difficulties. Research suggests children with speech language impairment (SLI) tend to have deficits in both verbal short-term memory and verbal working memory (e.g., Archibald & Gathercole, 2006). It is likely that many of the children with speech and/or language difficulties also experienced deficits in verbal short-term and working memory, which may explain the weaker relationships found between these two types of memory (i.e., verbal short-term memory and verbal working memory) and long-term memory. The weaker

relationship found between verbal short-term memory and long-term memory may have also been related to the nature of the tasks used to measure these two types of memory. The tasks used to measure long-term memory primarily tapped explicit memory for semantic information, which is only one aspect long-term memory. Varying tasks measuring other aspects of these complex memory systems may have yielded different results. Furthermore, the instructions and tasks for the AWMA were presented in a foreign British accent, which may have placed an additional demand on children's language resources when completing the AWMA tasks (Alloway & Cockcroft, 2014; Bruce, To, & Newton, 2012). Notably, participants were not required to specify whether their disabilities/medical conditions had been diagnosed by a professional. Therefore, we cannot assume that all participants who were reported to have speech/language difficulties would have met criteria to be diagnosed with a receptive and/or expressive speech and/or language disorder by a speech-language pathologist. This issue will be discussed further in relation to future research.

Research question 2. The second research question posed: do children with higher working memory scores differ significantly from children with lower working memory scores on measures of long-term memory? It was predicted children with higher working memory scores would differ significantly from children with lower working memory scores on measures of long-term memory. Consistent with the predicted relationship, children with higher working memory scores demonstrated statistically significant differences from children with lower working memory scores on measures of long-term memory; this relationship was true for both verbal working memory and visual-spatial working memory, with medium and medium to large effect sizes, respectfully. In other words, long-term memory abilities appear to differ for children with stronger working memory skills and children with weaker working memory skills. This finding aligns with the findings from the first research question, which demonstrated significant positive relationships between performances on working memory tasks and long-term memory tasks.

Upon further investigation, it was found that neither higher verbal working memory scores nor lower verbal working memory scores were significantly related to long-term memory scores. In contrast, significant relationships were observed between higher visual-spatial working memory scores and long-term memory scores. On the other hand, lower visual-spatial working memory scores were not significantly related to long-term memory scores. This finding is

particularly interesting in relation to the findings from the first research question; it was found that verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and central executive were significantly related to long-term memory. Verbal short-term memory was the only variable that did not demonstrate a significant relationship to long-term memory. According to the findings associated with the second research question, the strength of the relationship between working memory and long-term memory may depend on the child's level of functioning in each area of working memory. This may be an important finding for educators and professionals who work with children with regards to planning interventions and strategies. For example, based on these results, a child with strong visual-spatial working memory will likely have strong long-term memory abilities. On the other hand, a child with strong verbal working memory may have weaker long-term memory abilities and may need additional support in this area. This issue will be discussed further with regards to implications of the current research.

Theoretical Implications

A number of memory models suggest a relationship between working memory and long-term memory (e.g., Baddeley 2000; Dehn, 2008). Baddeley's model of working memory (Baddeley, 2000; Baddeley & Hitch, 1974) is commonly employed as the theoretical foundation in studies of children's memory (e.g., Alloway et al., 2006; Schuchardt et al., 2008). Baddeley's model includes four components: (a) the phonological loop; (b) the visual-spatial sketchpad; (c) the central executive; and (d) the episodic buffer. The episodic buffer is the component that takes into account the contribution of long-term memory within the working memory model. It is thought to integrate representations from components of working memory and long-term memory into unitary representations that may be accessed by the central executive during conscious experience (Baddeley, 2000). Based on the function of the episodic buffer, the findings from the current study, which demonstrated a significant relationship between working memory and long-term memory, appear to align with Baddeley's (2000) model. In fact, verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and the central executive all demonstrated significant relationships with long-term memory.

The Integrated Model of Working Memory (Dehn, 2008) suggests short-term memory, working memory, and long-term memory are all independent types of memory that are constantly interacting with one another. In this model, working memory is more closely linked

with long-term memory than with short-term memory (Dehn, 2008). Although working memory communicates with short-term memory, more of its resources are devoted to long-term memory (Dehn, 2008). The findings from the current study appear to align with the structure of Dehn's (2008) model; however, according to the current findings, working memory did not demonstrate a clear advantage over short-term memory with regards to its relationship to long-term memory, based on the measures that were used for the larger study (Marche et al., 2015). Rather, visual-spatial short-term memory and visual-spatial working memory demonstrated the strongest relationships to long-term memory. This finding may have been due to the nature of the tasks used to measure working memory and long-term memory. Alternatively, the stronger relationships between the visual-spatial domains with long-term memory than the verbal domains may have been due to the fact that parents of 29% of the participant sample identified their child as having speech/language difficulties (Marche et al., 2015). Notably, the identified speech/language difficulties were based on the parents' reports, and may or may not have been diagnosed by a speech-language pathologist. Nevertheless, the overall findings from the current study appear to support Dehn's (2008) model.

Implications for Practice

The positive relationships found between children's working memory and long-term memory may have practical implications for professionals working with children (e.g., school administrators, classroom teachers, special education teachers, psychologists, etc.) in school environments. Given the results of the current research, which suggest a significant relationship between working memory and long-term memory, there is reason to believe interventions effective for improving children's working memory (e.g., Cogmed; Pearson, 2015) may also improve their long-term memory, which would likely have a positive impact on their academic learning and development. Working memory functioning is important in order for children to perform many academic skills, such as following instructions and mental arithmetic (St Clair-Thompson, 2010). Many professionals utilize working memory interventions, such as computerized training programs and teaching strategies in order to help children improve their working memory (e.g., Cogmed; Pearson, 2015). Computerized working memory training has been found to improve other cognitive processes related to working memory (e.g., Jaeggi et al., 2008). Based on this information, improving children's working memory may also help to improve their long-term memory. School professionals and administrators can use this

information to make informed decisions about which interventions to promote and invest in for their school.

Findings from the current research also demonstrated the relationship between working memory and long-term memory may vary, depending on the child's level of working memory functioning. Specifically, higher and lower verbal working memory scores and lower visual-spatial working memory scores did not demonstrate significant relationships with long-term memory. In contrast, the relationship between higher visual spatial working memory scores and long-term memory was significant. Therefore, results from the current research suggest children with strong visual-spatial working memory may see the most long-term memory benefits from computerized working memory training (e.g., Cogmed; Pearson, 2015). It is worth noting that the sample size for the aforementioned correlations was small, which may partly explain the lack of statistical significance found between higher and lower verbal working memory, lower visual-spatial working memory, and long-term memory. As such, these children may still see long-term memory benefits from working memory training. Importantly, the study from which the current data was extracted (Marche et al., 2015) is investigating whether Cogmed (Pearson, 2015) may improve children's long-term memory. Depending on the findings from that research (Marche et al., 2015), there may be further support for the notion that working memory interventions have the potential to improve long-term memory.

The latter point may also apply to the way educators teach memory strategies to children in the classroom. Based on the results of the current study, which demonstrated significant relationships between children's working memory and long-term memory, there is reason to believe teaching children working memory strategies may improve both working memory and long-term memory. In fact, the literature suggests many instructional strategies designed to improve working memory may also improve long-term storage and retrieval (Banikowski & Mehring, 1999; Dehn, 2008). For example, elaborative rehearsal (i.e., associating new information with prior knowledge) makes information more meaningful, which helps keep information active in working memory and also increases the probability of retaining the information in long-term memory (Banikowski & Mehring, 1999; Dehn, 2008). Generally, working memory strategies, especially those that require meaningful learning, organization, and elaboration, will serve to enhance both working memory and long-term memory (Banikowski & Mehring, 1999). The study from which the current data was extracted (Marche et al., 2015) is

investigating whether teaching working memory strategies has the potential to improve children's long-term memory. Given the results of the current research, children with strong visual-spatial working memory may see the most long-term memory benefits from working memory strategy training. With this in mind, educators may need to focus on interventions designed to target the specific areas of the child's working memory or long-term memory they aim to improve.

Limitations

There were three main limitations in the current study. First, the participant sample extracted from the larger SSHRC funded study (Marche et al., 2015) was small. This small sample size limits the generalizability of the findings. According to sample size calculations completed prior to data analysis, 28 participants were needed in order to detect large effect and 85 participants were needed in order to detect medium effects. The total sample size of 41 for the current study was likely large enough to detect medium to large effects for the first research question; however, the analyses for the second research question included sample sizes ranging from 17 to 24 participants. As such, the small sample sizes used for the second research question may have contributed to the lack of statistical significance found in some of the results. Of the 41 participants included in the current study, 34 (82.9%) identified their ethnicity as Caucasian. Therefore, the results of this study may have limited generalizability to other ethnicities such as Aboriginal, Black, and Hispanic. Additionally, parents identified a number of participants as having a disability (e.g., speech/language difficulties; learning disability); therefore, the sample would not be an accurate representation of the general population.

The second limitation is related to the scope of the AWMA (Alloway, 2007). The AWMA (Alloway, 2007) does not provide a score for the central executive component of working memory. According to Baddeley (2012), the central executive is an important component of the working memory model, as it is responsible for controlling the actions of the phonological loop and the visual-spatial sketchpad. In order to generate an estimate of central executive functioning, the researcher calculated the average between verbal working memory and visual-spatial working memory scores; however, this measure can only be considered an estimate and not a standardized measure of central executive functioning. Further, the estimate only represents a small aspect of this complex system. The inclusion of a standardized measure

of the central executive would have provided a more comprehensive evaluation of participants' working memory functioning.

The third limitation is related to the normative samples used in the standardization of the two measures (i.e., AWMA & WJ-COG-III) used in the larger SSHRC funded study from which the data for this study was extracted (Marche et al., 2015). Specifically, the AWMA used a normative sample from the United Kingdom and the WJ-COG-III (Woodcock et al., 2001) used a normative sample from the United States. The data used in the secondary analyses in this study were from participants who were residents of Canada (Marche et al., 2015); therefore, using measures with Canadian normative samples, such as the Wechsler Intelligence Scale for Children – Fifth Edition (Wechsler, 2014), may have been more appropriate. Alloway and Cockcroft's (2014) research demonstrated children from different parts of the world might perform differently on measures of working memory. Nevertheless, all of the participants in the larger study completed all of the same measures (Marche et al., 2015). Therefore, the results of the current analyses still represent the relationship between participants' working memory and long-term memory scores.

Implications for Future Research

The relationship between children's working memory and long-term memory is an area of research in need of further exploration. Future research using larger sample sizes could explore potential variables that may mediate the relationship between working memory and long-term memory, such as the presence of ADHD or SLI. Martinussen and colleagues (2005) found that working memory is impaired in children with ADHD, especially in visual-spatial domains, compared to normal controls. Comparatively, Kaplan and colleagues (1998) found that children with ADHD perform equally as well as normal controls on measures of long-term storage and retrieval. Therefore, it may be important to consider the potential impact of ADHD on the relationship between children's working memory and long-term memory. Furthermore, Archibald and Gathercole (2006) found that verbal short-term and working memory tends to be impaired in children with specific language impairment (SLI). Therefore, it may also be important to consider the potential impact of speech and language disorders identified by a speech-language pathologist on the relationship between children's working memory and long-term memory. Overall, it would be beneficial for future research to investigate whether other

factors, such as age, gender, and the presence of disabilities (e.g., ADHD, SLI) may affect the relationship between children's working memory and long-term memory.

Conclusion

A relationship between working memory and long-term memory systems has been implied by a number of widely accepted memory models (e.g., Baddeley, 2000; Dehn, 2008); however, there is a lack of empirical research measuring this relationship using standardized assessment tools. Further, there are no available studies measuring this relationship in children. This is a critical area of research, as this information may be used to guide intervention strategies (e.g., computerized working memory training) for children struggling with academic performance.

This study utilized secondary data from a larger SSHRC funded study to investigate the relationships between children's working memory (i.e., verbal working memory, visual-spatial working memory, verbal short-term memory, visual-spatial short-term memory, and the central executive) and long-term memory using standardized assessment tools. Statistically significant correlations were observed between four areas of working memory (i.e., verbal working memory, visual-spatial working memory, visual-spatial short-term memory, and the central executive) and long-term memory. Mann-Whitney tests revealed children with higher working memory abilities differ significantly from children with lower working memory abilities on measures of long-term memory. The relationship observed between working memory and long-term memory appears to align with widely accepted memory models. The findings also suggest interventions designed to improve children's working memory may have the potential to enhance long-term memory abilities. The small sample size limited the generalizability of the findings and prevented the investigation of potential mediating variables (i.e., age, gender, ADHD) in the relationship between children's working memory and long-term memory. Future research would benefit from further exploration of the relationship between children's working memory and long-term memory utilizing large samples and diverse populations.

References

Alloway, T. P. (2007). *Automated Working Memory Assessment*. San Antonio, TX: The Psychological Corporation.

Alloway, T. P., Banner, G. E., & Smith, P. (2010). Working memory and cognitive styles in adolescents' attainment. *British Journal of Educational Psychology, 80*, 567-581. doi: 10.1348/000709910X494566

Alloway, T. P., & Cockcroft, K. (2014). Working memory in ADHD: A comparison of british and south african children. *Journal of Attention Disorders, 18*, 286-293. doi: 10.1177/1087054711417397

Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliot, J. (2008). Evaluating the validity of the Automated Working Memory Assessment. *Educational Psychology: An International Journal of Experimental Educational Psychology, 78*, 725-734. doi: 10.1080/01443410802243828

Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliot, J. (2009). The cognitive and behavioral characteristics of children with low working memory, *Child Development, 80*, 606-621. doi: 10.1111/j.1467-8624.2009.01282.x

Alloway, T. P., Gathercole, S. E., Willis, C., & Adams, A. M. (2004). A structural analysis of working memory and related cognitive skills in early childhood. *Journal of Experimental Child Psychology, 87,* 85–106. doi: 10.1016/j.jecp.2003.10.002

Alloway, T.P., Gathercole, S.E., & Pickering, S.J. (2006). Verbal and visuo-spatial short-term and working memory in children: Are they separable? *Child Development, 77,* 1698–1716. doi: 10.1111/j.1467-8624.2006.00968.x

Altmeyer, M., Schweizer, K., Reiss, S., Ren, X., & Schreiner, M. (2013). An account of performance in accessing information stored in long-term memory: A fixed-links model approach. *Learning and Individual Differences, 24*, 126-133. doi: 10.1016/j.lindif.2012.12.019

Archibald, L. M. D., & Gathercole, S. E. (2006). Short term and working memory in specific language impairment. *International Journal of Language and Communication Disorders, 41*, 675-693. doi: 10.1080/13682820500442602

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control

    processes. In K. Spence, & J. Spence (Eds.). *The Psychology of Learning and Motivation,*

    Vol. 2. (pp. 89-105).

Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental*

    Psychology Section A: Human Experimental Psychology, 5-28. doi: 10.1080/713755608

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in*

    Cognitive Sciences, 4, 417-423. doi: 10.1016/S1364-6613(00)01538-2

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of*

    Psychology, 63, 1-29. doi: 10.1146/annurev-psych-120710-100422

Baddeley, A., & Hitch, G. (1974). Working memory. In G. Brower (Ed.). *The psychology of*

    learning and motivation: Advances in research and theory (Vol. 8, pp. 47-89). New

    York: Academic Press.

Baddeley, A. D., Papagno, C., & Valler, G. (1988). When long-term memory depends on short-

    term storage. *Journal of Memory and Language, 27*, 586-595. doi: 10.1016/0749-

    596X(88)90028-9

Banikowski, A. K., & Mehring, T. A. (1999). Strategies to enhance memory based on brain

    research. *Focus on Exceptional Children, 32*(2), 1-16. Retrieved from http://proquest.com

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions:

    Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*, 65-94. doi:

    org/10.1037/0033-2909.121.1.65

Berninger, V., & Richards, T. (2002). *Brain literacy for educators and psychologists*. San Diego,

    CA: Academic Press.

Blumfeld, R. S., & Ranganath, C. (2006). Dorsolateral prefrontal cortex promotes long-term

    memory formation through its role in working memory organization. *Journal of*

    Neuroscience, 26, 916-925. doi: 10.1523/JNEUROSCI.2353-05.2006

Brown, D. A., & Hulme, C. (1996). Nonword repetition, STM, and word age-of-acquisition: A

    computational model. A model and a method. In S. E. Gathercole (Ed.), *Models of short-*

    term memory (pp. 129-148). East Sussex, UK: Lawrence Erlbaum.

Bruce, C., To, C., & Newton, C. (2012). Accent on communication: the impact of regional and

    foreign on comprehension in adults with aphasia. *Disability and Rehabilitation, 34*, 1024-

    1029. doi: 10.3109/09638288.2011.631680

Dehn, M. (2008). *Working memory and academic learning: Assessment and intervention.* Hoboken, NJ: John Wiley and Sons.

Dunn, L., & Dunn, D. (2007). *Peabody Picture Vocabulary Test* (4th ed.). Minneapolis, MN: Pearson.

Field, A. (2009). *Discovering Statistics Using SPSS, Third Edition.* London, UK: SAGE Publications Inc.

Flanagan, D. P., & Harrison, P. L. (2012). *Contemporary Intellectual Assessment: Theories, Tests, and Issues*. New York: The Guilford Press.

Floyd, R. G., Evans, J. J., & McGrew, K. S. (2003). Relations between cattell-horn-carroll (CHC) cognitive abilities and mathematics achievement across the school years. *Psychology in the Schools, 40*, 155-171. doi: 10.1002/pits.10083

Gathercole, S., & Alloway, T. (2007). *Understanding Working Memory: A Classroom Guide*. London: Harcourt.

Gathercole, S., Alloway, T, Willis, C, & Adams, A. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology, 93*, 265-281. doi: 10.1016/j.jecp.2005.08.003

Gathercole, S., Lamont, E., & Alloway, T. (2006). Working memory in the classroom. In S. J. Pickering (Ed.), *Working memory and education* (pp. 219-240). Burlington, MA: Academic Press.

Gathercole, S. E., & Martin, A. J. (1996). Interactive processes in phonological memory. A model and a method. In S. E. Gathercole (Ed.), *Models of short-term memory* (pp. 73-100). East Sussex, UK: Lawrence Erlbaum.

Gathercole, S. E., Pickering, S. J., Knight, C., & Stegmann, Z. (2004). Working memory skills and educational attainment: Evidence from national curriculum assessments at 7 and 14 years of age. *Applied Cognitive Psychology, 18,* 1-16. doi: 10.1002/acp.934

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological and genetic components. *Psychological Bulletin, 114*, 345-362. doi: 10.1037/0033-2909.114.2.345

Gibson, B. S., Kronenberger, W. G., Gondoli, D. M., Johnson, A. C., Morrissey, R. A., & Steeger, C. M. (2012). Component analysis of simple span vs. complex span adaptive working memory exercises: A randomized, controlled trial. *Journal of Applied Research in Memory and Cognition, 1*, 179-184. doi: 10.1016/j.jarmac.2012.06.005

Gill, C., Klecan-Aker, J., Roberts, T., & Fredenburg, K. (2003). Following directions: Rehearsal and visualization strategies for children with specific language impairment. *Child Language Teaching and Therapy, 19*, 85-103. doi: 10.1191/0265659003ct245oa

Glass, G. V., & Hopkins, K. D. (1996). *Statistical methods in education and psychology (3rd ed.).* Needham Heights, MA: Allyn & Bacon.

Holmes, J., Gathercole, S., Place, M., Dunning, D., Hilton, K., & Elliot, J. (2010). Working memory deficits can be overcome: Impacts of training and medication on working memory in children with ADHD. *Applied Cognitive Psychology, 24*, 827-836. doi: 10.1002/acp.1589

Horn, J. L., & Blankson, N. (2005). Foundations for better understanding of cognitive abilities. In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (2nd ed., pp. 41-68). New York, NY: Guilford Press.

Hulme, C., Maughan, S., & Brown, G. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language, 30*, 685-701. doi: 10.1016/0749-596X(91)90032-F

IBM Corporation. (2015). IMB SPSS Statistics. Retrieved from http://www.ibm.com

Imbo, I., & Vandierendonck, A. (2007). The development of strategy use in elementary school children: Working memory and individual differences. *Journal of Experimental Child Psychology, 96*, 284-309. doi: 10.1016/j.jecp.2006.09.001

Jacobs, J. (1887). Experiments on "prehension." *Mind, 12,* 75–79. Retrieved from http://www.jstor.org/stable/2246990

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, 105*, 6829-6833. doi: 10.3758/s13423-014-0699-x

James, W. (1890). *The principles of psychology*. New York: Henry Holt.

Jonides, J., Lacey, S. C., & Nee, D. E. (2005). Processes of working memory in mind and brain. *Current Directions in Psychological Science, 14,* 2–5. doi: 10.1111/j.0963-7214.2005.00323.x

Kane, M.J., Hambrick, D.Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., & Engle, R.W. (2004). The generality of working-memory capacity: A latent-variable approach to verbal and

visuo-spatial memory span and reasoning. *Journal of Experimental Psychology: General, 133,* 189–217. doi: 10.1037/0096-3445.133.2.189

Kaplan, B. J., Dewey, D., Crawford, S. G., & Fisher, G. C. (1998). Deficits in long-term memory are not characteristic of ADHD. *Journal of Clinical and Experimental Neuropsychology, 20*, 518-528. doi: 10.1076/jcen.20.4.518.1477

Klingberg, T., Fernell, E., Olesen, P., Johnson, M., Gustafsson, P., Dahlstrom, K., … Westerberg, H. (2005). Computerized training of working memory in children with ADHD: A randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry, 44*, 177-186. doi: 10.1097/00004583-200502000-00010

Klingberg, T., Forrssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology, 24*, 781-791. doi: 10.1076/jcen.24.6.781.8395

Leahey, T. H., & Harris, R. J. (1989). *Human learning* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Learning Disabilities Association of Saskatchewan. (2014). Retrieved from https://www.ldas.org/

Logie, R. (1996). The seven ages of working memory. In J. Richardson, R. Engle, L. Hasher, R. Logie, E. Stoltzfus, & R. Zacks (Eds.). *Working memory and human cognition* (pp. 31-65). New York: Oxford University Press.

Marche, T., McIntyre L., & Claypool, T. (2015). [Improving children's working memory with cogmed and strategy training]. Unpublished raw data.

McGrew, K. S. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence, 37*, 1-10. doi: 10.1016/j.intell.2008.08.004

Murray, B. (2010). *The combined and differential roles of working memory mechanisms in academic achievement* (Unpublished doctoral dissertation). Indiana University of Pennsylvania, Indiana, PA.

Paas, F., Renkl, A., & Sweller, J. (2004). Cognitive load theory: Instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science, 32*, 1-8. doi: 10.1023/B:TRUC.0000021806.17516.d0

Pearson Education. (2015). Cogmed Working Memory Training. Retrieved from
 http://www.cogmed.com/

Ranganath, C., Johnson, M. K., & D'Esposito, M. (2003). Prefrontal activity associated with
 working memory and episodic long-term memory. *Neuropsychologia, 41*, 378-389. doi:
 S0028-3932(02)00169-0

Rizza, M. G., McIntosh, D. E., & McCunn, A. (2001). Profile analysis of the woodcock-johnson
 III tests of cognitive abilities with gifted students. *Psychology in the Schools, 38*, 447-
 455. doi: 10.1002/pits.1033

Sattler, J. M. (2008). *Assessment of children: Cognitive foundations (5th ed.).* La Mesa, CA:
 Jerome M. Sattler, Publisher, Inc.

Schuchardt, K., Maehler, C., & Hasselhorn, C. (2008). Working memory deficits in children with
 specific learning disorders. *Journal of Learning Disabilities, 41*, 514-523. doi:
 10.1177/0022219408317856

Smith-Spark, J. H., & Fisk, J. E. (2007). Working memory functioning in developmental
 dyslexia. *Memory, 15*, 34-56. doi: 10.1080/09658210601043384

St Clair-Thompson, H. L., & Gathercole, S. E., (2006). Executive functions and achievements in
 school: Shifting, updating, inhibition, and working memory. The Quarterly Journal of
 Experimental Psychology, 59, 745-759. doi: 10.1080/17470210500162854

St Clair-Thompson, H., Stevens, R., Hunt, A., Bolder, E. (2010). Improving children's working
 memory and classroom performance. *Educational Psychology: An International Journal
 of Experimental Educational Psychology, 30*, 203-219. doi:
 10.1080/01443410903509259

Swanson, H. L., Howard, C. B., & Saez, L. (2006). Do different components of working memory
 underlie different subgroups of reading disabilities? *Journal of Learning Disabilities, 29*,
 252-269. doi: 10.1177/00222194060390030501

Swanson, H., & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in
 children with learning disabilities: Both executive and phonological processes are
 important. *Journal of Experimental Child Psychology, 79*, 294-321. doi:
 10.1006/jecp.2000.2587

Swanson, H., & Siegal, L. (2001). Learning disabilities as a working memory deficit. *Issues in Education: Contributions from Educational Psychology, 7*, 1-48. Retrieved from http://ebsco.com

Taub, G. E., Floyd, R. G., Keith, T. Z., McGrew, K. S. (2008). Effects of general and broad cognitive abilities on mathematics achievement. *School Psychology Quarterly, 23*, 187-198. doi: 10.1037/1045-3830.23.2.187

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children (4th ed.).* Toronto, ON: Pearson.

Wechsler, D. (2014). *Wechsler Intelligence Scale for Children (5th ed.).* Toronto, ON: Pearson.

Wilkinson, G. S., & Robertson, G. J. (2006). *Wide Range Achievement Test (4th ed.).* Lutz, FL: Psychological Assessment Resources.

Woodcock, R., McGrew, K., & Mather, N. (2001a). *Woodcock-Johnson* (3rd ed.). Itasca, IL: Riverside Publishing.

Woodcock, R. McGrew, K. & Mather, N. (2001b). *Woodcock-Johnson III Tests of Achievement.* Itasca, IL: Riverside Publishing.

Woodcock, R. McGrew, K. & Mather, N. (2001c). *Woodcock-Johnson III Tests of Cognitive Abilities.* Itasca, IL: Riverside Publishing.