The Relations between Working Memory and Mathematics Achievement of Children in the Primary Grades

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Abstract

This study investigated the predictive relations between working memory in Kindergarten and mathematics achievement in first and second grade. The research is underpinned by Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) and places particular emphasis on the roles of the central executive and the phonological loop components of the working memory system. A sample consisted of 92 participants (age range: 4 years, 4 months to 6 years, 5 months). Measures of vocabulary, working memory, and phonological processing were administered to children in Kindergarten and their early numeracy, mathematics word-problem solving, and knowledge of mathematical concepts were assessed in first and second grade. Results from hierarchical regression analyses showed the central executive of Baddeley's model is important to explanations of children's early numeracy and their emerging knowledge of mathematical concepts, whereas processing affiliated with the phonological loop explains first grade early numeracy and second grade mathematics word-problem solving. Implications of the study findings for early screening for children at risk for mathematics learning disabilities are discussed.

Keywords: working memory; mathematics achievement; elementary school

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Table of Contents

List of Tables

Chapter 1.

Introduction

A substantial body of research has focused on identifying the cognitive processes that predict mathematics achievement of older children in the elementary school years. Collectively, study findings support the idea that performance on measures of working memory executive system (Barnes et al., 2014; Berg, 2008; Geary, Hoard, Nugent, & Byrd-Craven, 2007), processing speed (Clark et al., 2014; Geary et al., 2007), and phonological awareness (Alloway, Alloway, & Wootan, 2014; Barnes et al., 2014; Hecht, Torgesen, Wagner, & Rashotte, 2001) contribute to children's emerging conceptual and procedural knowledge about mathematics, as well as their early numeracy and mathematics word-problem solving abilities (Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Swanson, 2006; Swanson, Jerman, & Zheng, 2008). While the corpus of studies mentioned above investigated the predictive relationships between working memory executive system, processing speed, phonological awareness, and mathematics achievement in children in the upper elementary grades, less is understood about these relations for children who are in the primary grades. The present study addresses this issue and examines whether the working memory system available to children in Kindergarten is predictive of their mathematics achievement at the end of the first and second grade. Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) multi-component model of working memory guides this research, specifically, the purpose of the research is to evaluate the relative influence of measures of the central executive and the phonological loop components within this model on children's emerging knowledge of quantitative concepts, the accuracy and speed at which calculations are performed and mathematics word-problem solving.

This chapter starts with an overview of Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory as the central executive and the phonological loop within this model are used to formulate hypothetical linkages between children's working memory and mathematics achievement. The second section of the chapter reviews research that is relevant to a discussion about linkages between the central executive and/or the phonological loop to conceptual and procedural knowledge about mathematics, their early numeracy and their mathematics word-problem solving for children in the primary grades. Several issues in this body of literature remain unresolved, and a discussion of these issues provides the impetus for the current research. The chapter concludes with the research questions and hypotheses that guide the present study.

1.1. Baddeley's Model of Working Memory

Baddeley and Hitch's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) multi-component model of working memory has been used extensively in research that explores the nature of the relations between working memory and mathematics achievement. Baddeley and Hitch originally proposed this model of working memory in 1974; it was revised by Baddeley in 1986, 1996, and 2000. Baddeley (2007) defines working memory as "a temporary storage system under attentional control that underpins our capacity for complex thought" (p.1). As opposed to short-term memory, which refers to the passive storage of information for brief periods of time, working memory directs attention to tasks and transfers new information to long-term memory. At the core of this model is the central executive, which represents an executive control system of fixed capacity. The phonological loop and the visual spatial sketchpad represent two lower level processing systems of linguistic and visual information respectively. More recently, Baddeley (2000) has included a fourth component, the episodic buffer, where the influence of conscious memory of experience on the working memory system is taken into account by linking long-term knowledge with current operational knowledge. While the emphasis of the current research is specifically on the role of the central executive and the phonological loop, the following discussion situates these two components in relation to the full model proposed by Baddeley.

1.1.1. The Central Executive

A primary component within the working memory system is the central executive. In Baddeley and Hitch's (1974) original model the central executive represents a general capacity to allocate and monitor attention and is conceived as having two subordinate systems for temporary storage and processing of information: the phonological loop and the visual-spatial sketchpad. Within this model, the central executive system is in direct contact with the two subordinate systems and coordinates the activity within the overall working memory system. The main role of the central executive component is focusing, dividing, and switching attention within the working memory system, along with overall activity coordination between the different components. Baddeley's (1986) later version of the model advanced the central executive in greater detail by dividing control between two processes—(a) control of behaviour by schemas, guided by environmental cues and (b) supervisory activation system, activated when control of attention to actions is not routine. Routine actions are controlled by schemas that are stable representations in long-term memory. For example a young child may be able to recite the numbers 1 to 10, yet have no conceptual understanding of the quantity represented by each number spoken. When the child is asked to manipulate the numbers in the sequence, such as providing numbers before or after a particular number, the supervisory activation system is enacted to attend to all possible solutions and choose the most suitable one. The central executive is seen as flexible and domain general (Baddelley, 1986). Further, Baddeley & Logie (1999) propose that several executive control processes are affiliated with the central executive, including the capacity to switch retrieval plans, to divide attention between two tasks performed simultaneously, and to control access to long-term memory.

Measures of the central executive are typically complex span tasks (e.g. de Smedt et al., 2009; Xenidou-Dervou, de Smedt, van der Schoot, & van Lieshout, 2013). In a study of relations between individual differences in children's working memory and reading, Daneman and Carpenter (1980) used a reading span task where children were required to read a series of sentences and then to recall the final word of each sentence in order. Henry (2011) argues that this task is directly comparable to short-term memory word span tasks in terms of the storage and output requirements. The difference, however, is that Daneman and Carpenter's reading span task requires children to process the words read in a sentence as they focus attention to the final word. That is, children are asked if a sentence is true or false before they are asked to state the last word of each sentence. By asking children to attend to the meaning of each sentence as well as the order of the last word in the series of sentences, short-term memory strategies such as verbal rehearsal to maintain a memory trace of the target item cannot be maintained.

Similarly, Zheng, Swanson, and Marcoulides (2011) used a listening span task where participants remember numerical, rather than lexical information embedded within a sentence. After presenting a short sentence (e.g. “Suppose somebody wanted to have you take them to the supermarket at 8651 Elm Street”), children were first asked a processing question about the name of the street, and then asked to recall the numbers of the address in the correct order. Interference from distractors is also incorporated to visual working memory tasks. For example, on a visual matrix task, Berg (2008) showed children a matrix of dots and then removed the matrix from view. The children were asked a question about the array of dots and then prompted them to reproduce the exact location of the dots on a blank matrix.

1.1.2. The Phonological Loop

The phonological loop in Baddeley’s model (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) is theoretically responsible for the temporary activation and processing of phonological representations activated and retrieved from long-term memory. The phonological information activated is related to either spoken language in the environment or to visual objects that are encoded by phonemes in a spoken lexicon; for example, when children are shown the visual representation of the numeral “6”, they may encode this visual symbol in long-term memory with a sequence of phonemes, [sɪks]. Baddeley and Hitch (1974) and Baddeley (1986, 1996, 2000) propose that the phonological loop consists of two basic subcomponents: a phonological store where speech-based, phonological information is temporarily activated, and an articulatory rehearsal process that maintains activation of this phonological information in working memory as it is simultaneously used in mental operations. Activation of phonological representations in the phonological store is influenced by the quality of children’s speech perception. The rehearsal of speech-based phonological information is equivalent to regulation of inner speech and is associated with the quality of children’s speech production. As long as speech-based phonological information is being repeated or rehearsed, it remains active in the phonological loop. Baddeley (2003) has implicated processing in the phonological loop as a major determinant of language acquisition. The assumption that verbal information is coded phonologically in the phonological loop of the working memory is supported by the presence of the phonological similarity effect, an outcome that occurs as lists of phonologically similar words are more difficult to remember than phonologically dissimilar words. Further, recall of lists of shorter words is typically better than recall of sequences of longer words, which implies that the capacity of the phonological loop is also influenced by the number of phonological codes to be recalled in a word.

Hecht et al. (2001) distinguish three types of processing in the phonological loop that are tapped by different measures: (a) phonological memory, which involves coding and short-term storage of sound-based representations; (b) phonological awareness; and (c) rate of access to phonological representations in long-term memory. Short-term memory tasks require the recall of digits (Passolunghi & Siegel, 2004, Swanson & Sachse-Lee, 2001), letters, words, and nonwords (Berg, 2008; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Passolunghi & Siegel, 2004) without competing, interfering information, such as the one that exists on measures of the central executive. Phonological awareness is measured by tasks that involve a response where children must first attend to and manipulate the sounds of speech (Passolunghi & Siegel, 2004; Swanson, 1999, 2004; Swanson et al., 2008). Measures of articulation speed are typically used to assess the fluidity of access to phonological representations in long-term memory (McDougall, Hulme, Ellis, & Monk, 1994). For example, in a study of mathematical problem solving in children in Grades 1 to 3, Swanson (2004) used measures of digit span, phonemic deletion, and articulation speed of words as measures of the phonological loop.

In contrast to Hecht et al.'s (2001) view that phonological short-term memory and phonological awareness are influenced by phonological processing and represent distinct cognitive systems, other theorists propose that phonological awareness and phonological short-term memory tap into the same construct (Passolunghi & Siegel, 2004).

In the present research, the role of the central executive and the phonological loop in the working memory system available to Kindergarten children is examined as a predictor of early mathematics achievement in the Grades 1 and 2. These two components of the working memory system are not fully developed in Kindergarten-aged children and whether measures of these components are reliable predictors of later mathematics achievement is not known. One possibility is that because the working memory system is emerging, access to resources affiliated with these components is not fluent, and therefore, predictions will be unstable. On the other hand, access to this evolving working memory system may be more robust than expected at this developmental stage, and therefore, predictions with later mathematics achievement will be statistically significant.

While the present study does not focus on the visual-spatial sketchpad or the episodic buffer, these two components of Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) are discussed to provide further context to the research.

1.1.3. The Visual-Spatial Sketchpad

The visual-spatial sketchpad is responsible for the temporary storage of visually and spatially coded information, such as remembering colours, location, and shapes of objects in scenes. The role of the visual-spatial sketchpad has also evolved since being initially introduced in Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) original model of working memory. Although distinctions are made between visual and spatial coding of information, the dynamic, static, and kinaesthetic dimensions of information are also thought to be important to processing in the visual-spatial sketchpad (Baddeley, 2003). Therefore, the visual-spatial sketchpad is viewed as a subsystem that integrates visual-spatial information from visual, tactile, and kinaesthetic sources, as well as from both episodic and semantic long-term memory (Baddeley, 2007). The visual-spatial sketchpad is limited in capacity to about three or four objects at a given time (Baddeley, 2003). Logie (1995) proposed a division of the visual-spatial sketchpad comparable to that of the structure of the phonological loop. He differentiated between two basic subcomponents: (a) a visual storage component, the visual cache, used to store visual characteristics of objects and events; and (b) a dynamic retrieval and rehearsal process, the inner scribe, used to deal with spatial and movement information, body sequences and movements, and image manipulation. The inner scribe is also responsible for the rehearsal and transfer of information from the visual cache to the central executive component.

The visual-spatial sketchpad is generally investigated by tasks requiring recall of locations (Berg, 2008; Geary et al., 2007; Passolunghi & Siegel, 2004). The Corsi Block Tapping Task (Corsi, 1972) is the most popular task for visual short-term memory used to index immediate memory span capacity for spatial information. The test consists of nine wooden blocks that are distributed over a board. In the test, the experimenter taps random sequences of series of blocks at the rate of one block per second. The sequences are progressively increasing in difficulty and the participant is asked to duplicate the tapping in the same sequence as the examiner.

1.1.4. The Episodic Buffer

The original three-component model of working memory proposed by Baddeley and Hitch (1979) could not explain how the central executive, phonological loop, and visual-spatial sketchpad interact together and with long-term memory. To address this issue, Baddeley (2000) proposed a fourth component, the episodic buffer, as “a temporary storage system that is able to combine information from the loop, the sketchpad, long-term memory, or indeed from perceptual input, into a coherent episode” (Baddeley, 2007, p. 148). The episodic buffer is controlled by the central executive. It is described as episodic, because information is integrated from the three working memory subcomponents and long-term memory into a unitary multi-dimensional episodic experience. The episodic buffer temporarily stores input from auditory, visual, and spatial modalities before integrating it with new information into a single complex episode. It is considered a buffer because it acts as an interface between the different subcomponents. Put another way, the episodic buffer is assumed to perform some of the operations initially assigned in Baddeley’s model to the central executive component, so that the central executive component becomes more of a regulatory, attentional system.

A limited number of studies have explored the nature of the episodic buffer in younger children (e.g., Alloway, Gathercole, Willis, & Adams, 2004; Henry, 2010; Klem et al., 2014; Michalczyk, Krajewski, Preβler, & Hasselhorn, 2013) with a range of developmentally appropriate, experimental tasks (see Nobre et al., 2013 for a review on episodic buffer tasks used across the life span). Alloway et al. (2004) used a sentence repetition task as a measure of the episodic buffer. The argument made is that repeating sentences involves binding of phonological information from the phonological loop with semantic and syntactic information. Tasks vary in complexity and can involve simple semantic and syntactic structures (e.g., “Five pencils are on the table.”) or a combination of semantic and syntactic structures that vary in complexity (e.g. “The five pencils on the table are larger than the three pencils in the backpack.”).

1.1.5. Baddeley's Model of Working Memory

In factor analyses with children, typically the three initial factors of Baddeley's (1986) model of working memory emerge. Gathercole, Pickering, Ambridge, and Wearing (2004) showed that the tripartite structural organization of Baddeley's working memory system (i.e., central executive, phonological loop, and visual-spatial sketchpad) is stable over the childhood years. In their study, children in five age groups (4-5 years; 6-7 years; 8-9 years; 10-12 years; 13-15 years) were administered measures of each working memory component. Confirmatory factor analyses were carried out corresponding to either a three-factor or two-factor model. For all age groups the three-factor model provided better fit for the data than the two-factor model. The three distinct but correlated factors corresponded to each component of Baddeley's model of working memory and all three components of children's working memory show linear increases in functional capacity from the age of six years. In a factor analysis conducted by Alloway et al. (2004), findings showed a factor representing the episodic buffer can be identified in a sample of children as young as four years of age.

In the present research, the role of the central executive and the phonological loop in Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) on young children's early mathematics achievement is explored. One possibility is that the central executive system is not fully operational for children of Kindergarten age; therefore lower level processing associated with the phonological loop may account for the strategies used by children to compute calculations or solve mathematical word-problems. On the other hand, research has shown that by the time children reach the age of seven years, they access cognitive resources associated with the central executive to solve mathematics word-problems (Swanson, 2007); therefore, it may be that the central executive is more important to constructing declarative or procedural knowledge about mathematics than the phonological loop. Specifically, this study explores whether a general executive predicts mathematics achievement beyond the contribution of phonological processing speed or phonological awareness in the phonological loop.

1.2. Mathematics Achievement

Mathematics achievement, as defined by Dowker (2005) is "knowledge of arithmetical facts; ability to carry out arithmetical procedures; understanding and using arithmetical principles . . . mathematical knowledge; applying arithmetic to the solution of word problems and practical problems" (p. 324). Of particular interest to the present study are outcomes related to *mathematics conceptual knowledge, mathematical computational abilities, the speed of making these mathematics computations,* and *language-based mathematics problem solving.* These outcomes are emphasized in the learning objectives within Kindergarten, first- and second-grade British Columbia's provincial mathematics curriculum (BC Ministry of Education, 2007) where the present research was conducted.

Mathematical conceptual knowledge is constructed from children's experience in both informal and formal learning situations. Knowledge constructed before or outside of school in informal, everyday situations is characterized by the use of nonconventional symbols, strategies, and procedures (Purpura, Baroody, & Lonigan, 2013). Once children enter school they engage in formal instruction and understanding of numeracy emerges (Passolunghi & Lanfranchi, 2012; Purpura & Ganley, 2014). Early numeracy is broadly defined here as the ability to draw upon conceptual knowledge about numeracy to perform simple mathematical calculations. For example, early numeracy includes knowing that each number in a counting sequence represents one more unit of measurement than the number preceding it, and that each number represents one less unit of measurement than the number following it (Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012). As children engage in experiences with others who use and perform operations with numbers, they also share linguistic symbols to make sense of these actions. Linguistic symbols affiliated with early numeracy can be spoken ('one', 'two') or written, such as numerical notation (e.g., Arabic numerals and operation or equality signs). A major focus of a primary mathematics curriculum is to provide children with the repeated experiences necessary for them to become fluent in the use of these linguistic, numerical symbols. Knowledge about simple mathematical operations and the numerical symbols that represent these operations is constructed early on, when children first enter school (Purpura et al., 2013).

As children progress through a primary grades curriculum, they construct more complex schemas for different types of calculations. These schematic representations of procedures or rules can be accessed and used directly, or used strategically as part of more complex calculations, such as in the process of "decomposition" (Geary et al., 2004). In decomposition, representations of known rules are accessed from long-term memory to simplify the procedures used in calculations that are unfamiliar. For example, a child may not have sufficient knowledge to calculate the sum of 8 and 2; however when the number 8 is “decomposed” to become the sum of 5 and 3, the child may know the sum of 5, 3, and 2 (Noël, Seron, & Trovarelli, 2004).

Multiplication strategies rely heavily on stable information retrieved from long-term memory (Imbo & Vandierendonck, 2008). In a longitudinal study of French children in Grade 1 through their second year of schooling, Lemaire and Siegler (1995) found that children became more efficient over time in their use of retrieval strategies when performing single-digit multiplication. Lemaire and Siegler (1995) suggested that accuracy is greater and speed of retrieval is faster when strong associations are made between a calculation and an accurate response early on in children’s learning. Multiplication and division are considered to be conceptually related operations and they follow a similar developmental course in young children (De Brauwer & Fias, 2009).

Solving mathematics word problems draws upon children’s understanding of early numeracy as well as their ability to process and understand verbally expressed propositions, build a problem model, and construct a calculation procedure, which is followed by problem execution (Cowan & Powell, 2014; Fuchs, Geary, Fuchs, Compton, & Hamlett, 2014). Empirical evidence from correlational studies indicates that the suite of cognitive resources accessed by children to compute calculations differs from those accessed to solve word problems (e.g. Fuchs et al., 2010; Meyer et al., 2010; Swanson, 2006).

Taken together, these study findings suggest that for children in primary grades, mathematics achievement is a multidimensional construct that includes different skills, such as computing calculations, solving mathematics word problems, and implementing these skills in new situations (Männamaa, Kikas, Peets, & Palu, 2012). Throughout this corpus of studies, mathematics achievement was assessed with norm-referenced, standardized measures. The Wechsler Individual Achievement Test (WIAT; Wechsler, 2001), Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock, McGraw, & Mather, 2001), and the Wide Range Achievement Test–Third Revision (WRAT–III; Jastak & Wilkinson, 1984) are the most widely used measures in studies of early mathematics performance (e.g., Fuhs, Nesbitt, Farran, & Dong, 2014; Hassinger-Das, Jordan, Glutting, Irwin, & Dyson, 2014; McClelland et al., 2007; Swanson & Kim, 2007). The three assessed domains were (a) children’s early numeracy, (b) their fluency (speed) of performing calculations, and (c) their ability to solve mathematics word problems (Barnes et al., 2014; de Smedt et al., 2009; Geary, 2011; Jerman, Reynolds, & Swanson, 2012; Swanson, 2011).

1.3. Working Memory and Mathematics Achievement

The relations between working memory and mathematics achievement in young children in the primary grades is a relatively recent topic of research, for the majority of studies have investigated these relations in older elementary school aged children. Baddeley’s model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) has guided much of this research, with the main question being whether the central executive (i.e., top-down processes) or the phonological loop/visual spatial sketchpad (i.e., bottom-up processes) within a working memory system is associated with unique domains of mathematics achievement. The following discussion emphasizes the limited research available that has investigated these relations among children in the primary grades.

1.3.1. The Central Executive

The central executive in Baddeley’s model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) appears to play a significant role in children’s early numeracy (e.g., Bull & Scerif, 2001; Holmes & Adams, 2006; Kroesbergen, van Luit, van Lieshout, van Loosboek, & van de Rijt, 2009; Noël, 2009; Simmons, Willis, & Adams, 2012) and mathematics word problem solving (e.g., Meyer et al., 2010).

Support for the view that learning to compute calculations in the primary grades draws upon an executive working memory system is robust. Fuchs et al. (2010) found that among children in first grade the contribution of the verbal working memory to computational abilities was statistically significant. Moreover, in a longitudinal study of children from Grades 1 to 3, Fuchs and colleagues (Fuchs et al., 2014) investigated the role of the central executive in Baddeley’s model of working memory on numeration understanding and calculation of multi-digit addition and subtraction problems after controlling for mathematical conceptual knowledge, visual-spatial reasoning, listening comprehension, and attentive behaviour. Findings showed that after controlling for conceptual knowledge, the direct effects of verbal working memory, visual-spatial reasoning, and attentive behaviour on first grade numeration understanding were all statistically significant. However, of these three cognitive abilities, only attentive behaviour in first grade predicted children's computational ability in third grade. Fuchs et al. (2014) interpreted these findings as evidence that shows the central executive is associated with children's early numeracy in the first grade, after controlling for their knowledge of mathematics concepts. However, these relations are not predictive of later computational abilities in third grade.

Although there is a general consensus that the central executive supports the learning of novel tasks such as computing calculations in the primary grades, the relations between central executive and mathematical word problem solving are unclear.

For example, Fuchs et al. (2010) used two tasks to assess the contribution of the central executive component of Baddeley's model of working memory to first graders' ability to solve spoken mathematics word problem. They found that while the listening span task made statistical contribution to mathematics word problem solving, the counting span task did not. Fuchs et al. (2010) questioned whether the two tasks were equal measures of the central executive for first graders.

Moreover, Meyer et al. (2010) examined the contribution of an executive working memory system to second graders' ability to solve spoken mathematics word problems. Findings were somewhat difficult to interpret, as some, but not all measures of the central executive contributed to mathematics word problem solving. That is, the contribution of counting recall to variance in word problem solving was statistically detectible; however, the influence of backward digit span was not statistically significant. Meyer and colleagues (2010) attributed these differences to variation in task demands: counting recall requires children to retrieve numerical information from long-term memory into working memory whereas backward digit recall requires both the retrieval and the manipulation of numerical information. Accordingly, these findings suggest that it is the retrieval of information from long-term memory into a working memory executive system, rather than the processing of information at the executive level per se that accounts for the relations with mathematics word problem solving in young children.

Alternatively, Swanson (2011) argues that growth in working memory capacity in general, which includes both the central executive and the phonological loop influences growth in mathematics word problem solving. Findings from longitudinal research on children as they progressed from Grade 1 to Grade 3 and that contrasted four opposing models found that visual working memory at the level of the central executive and the phonological loop in first grade together influence mathematics word problem solving in grade three, beyond the contribution of inattention, inhibition, rapid naming speed, phonological awareness, and reading achievement.

Taken together these findings lead to the prediction that in young children in the primary grades visual working memory at the level of the central executive may be a more stable predictor of later mathematics word problem solving than verbal working memory. In the present research measures of verbal and visual working memory were administered to children in Kindergarten to investigate whether relations between the central executive and mathematics word problem solving are domain-general or specific to the visual domain.

1.3.2. The Phonological Loop

1.3.2.1 Processing Speed in the Phonological Loop

It is well established that during the primary grades (i.e., Grades 1 to 3), children's rate of processing verbal or visual information is associated with their ability to perform computations (Berg, 2008; Georgiou, Tziraki, Manolitsis, & Fella, 2013; Koponen, Aro, Räsänen, & Ahonen, 2007; Koponen, Mononen, Räsänen, & Ahonen, 2006; Koponen, Salmi, Eklund, & Aro, 2014; Swanson & Kim, 2007) and their ability to solve mathematics word problems (Swanson, 2011; Swanson & Beebe-Frankenberger, 2004).

Moreover, these associations remain robust after taking into account individual variability due to processing at the executive level within a working memory system (Hecht et al., 2001; Swanson & Kim, 2007). Processing speed is typically assessed with the use of rapid automatized naming tasks that require individuals to quickly name familiar symbols such as objects, colours, pictures, letters, and digits.

Five longitudinal studies report findings relevant to a discussion of the relations of processing speed and children's mathematics competencies in the early years of school. Each study investigated these relations during a different segment of time between preschool to third grade. Clark et al. (2014) investigated the role of processing speed within a working memory system to preschoolers' early numeracy; Passolunghi and Lanfranchi (2012) examined developmental relations between processing speed and early numeracy over the Kindergarten year; Cirino (2011) assessed the relations between the rate of processing linguistic information and first graders' ability to compute calculations; Georgiou et al. (2013) investigated the contribution of processing speed at the beginning of the Kindergarten year to early reading and early numeracy over the following two years; Swanson (2011) also provides evidence of the importance of processing speed to mathematics word problem solving over Grades 1 to 3.

Clark et al. (2014) investigated whether the processing speed of preschoolers predicts their later performance on standardized measures of mathematics achievement. The study included 388 preschoolers who were tested every nine months from the time they were three years old until they were 5.25 years old. The Visual Matching Test from the Woodcock-Johnson Test of Cognitive Abilities (Woodcock et al., 2001) was used as a direct measure of processing speed. Mathematics achievement was assessed with the Test of Early Mathematics Ability-3 (TEMA–3; Ginsburg & Baroody, 2003) (i.e., numeric concepts, including magnitude comparison, non-verbal addition and subtraction, cardinality, part-whole relationships, mathematic symbol recognition, counting) and the Applied Problems subtest (problem solving) from the Woodcock-Johnson III Tests of Achievement (Woodcock et al., 2001). Processing speed administered in pre-school was found to be a strong predictor of mathematics achievement across the preschool and Kindergarten years. Clark et al. (2014) concluded that processing speed is a central limiting mechanism that influences preschool children's abilities to quickly retrieve representations of digits, shapes, and operations from long term memory that are critical for early numeracy.

Passolunghi and Lanfranchi (2012) explored early numeracy skills and processing speed in young children as they progressed from Kindergarten to first grade. Mathematics achievement was assessed with a standardized Italian mathematics test for primary students. The test was divided into three sections: logic, arithmetic, and geometry. The logic section tested spatio-temporal analysis, seriation, and classification; the arithmetic section tested number concepts and understanding of basic arithmetic operations (i.e., +, -); and the geometry section tested simple topology (i.e., identifying paths in mazes). Children were tested at three time points—at the beginning and at the end of their last year of Kindergarten and at the end of their first year of primary school. Early numeracy was assessed at the first time point, processing speed was evaluated at the second time point, and logic, arithmetic, and geometry skills were evaluated in Grade 1. Processing speed in Kindergarten predicted logic, arithmetic, and geometry skills in first grade.

Cirino's research (2011) revealed that the linguistic pathway in LeFevre and colleagues' (2010) model of mathematical cognition predicted first graders' ability to calculate single-digit addition problems. The linguistic pathway includes processing speed and phonological awareness, which correspond to processes in the phonological loop of Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory.

Georgiou and colleagues' (2013) study is the only one that has investigated which rapid automatized naming (RAN) components (articulation time and/or pause time) predicts reading and mathematics and which cognitive skills associated with RAN (speed of processing, working memory, phonological awareness) explain RAN's relationship with reading and mathematics. Seventy two Greek children were followed from the beginning of Kindergarten until the end of Grade 1 and were assessed on measures of general cognitive ability, speed of processing, rapid automatized naming (Color Naming and Object Naming), working memory (Word Series and Corsi frog), phonological awareness (Initial Sound Identification and Syllable Segmentation), reading, and mathematics. With the exception of the reading and mathematics measures that were administered at the end of Kindergarten and at the end of first grade, the remaining measures were administered at the beginning of Kindergarten. With respect to mathematics, after controlling for general cognitive abilities, findings showed that not the articulation time component of rapid automatized naming but the duration of pause time component explained unique variance in cardinality, seriation of numbers, naming of single-digit numbers, number comparison, verbal counting in Kindergarten and calculation fluency in first grade. However, after controlling for general cognitive ability, speed of processing, and visual-spatial memory, the pause time component of rapid automatized naming did not explain any unique variance in cardinality, seriation of numbers, naming of single-digit numbers, number comparison, verbal counting in Kindergarten and calculation fluency in first grade.

Swanson (2011) reports that performance in Grade 1 on measures of naming speed predicts mathematics word problem solving accuracy in Grade 3 when measures of long-term memory, attention, and phonological processing are recognized. Swanson and Beebe-Frankenberger (2004) also acknowledge the relationship between processing speed, word problem solving, and computation ability in six to eight year-old students who were at risk for developing mathematics learning disabilities.

Taken together, the findings provide evidence that the central executive is important to both early numeracy and mathematics word problem solving at different time points over the primary grades; however, whether these mathematical outcomes in grade one and two can be predicted from Kindergarten performance on working memory measures is unclear. The present research addresses this issue by examining whether measures of the central executive taken in Kindergarten predict later numeracy skills and mathematics word problem solving in first and second grade.

1.2.2.2. Phonological Awareness in the Phonological Loop

Phonological awareness, defined here as the ability to attend to and manipulate the sounds of a spoken language (Snow, Burns, & Griffin, 1998) is thought to play an important role in processing associated with the phonological loop of Baddeley's model of working memory. At birth, preverbal infants are well equipped to attend to variation in the speech signals they hear around them, regardless of the languages spoken. As they gain experience with their languages, representations of the phonological codes associated with these languages are constructed in long-term memory. At first, these phonological codes are poorly formed and lack specificity. However, with continued experience attending to the speech of others and speaking themselves, young children become reflexively aware of the phonological systems that represent the spoken languages in their local community. Phonological awareness is also enhanced when children enter school and receive reading instruction that includes activities aimed at mapping the sounds of speech to orthographic symbols.

According to the weak phonological representations hypothesis put forward by Simmons and Singleton (2008), when children have poorly specified phonological representations in long-term memory due to unfamiliarity or lack of experience with a spoken language system, the rate of access to these phonological codes is slower, which in turn results in slow and inaccurate performance on early numeracy tasks. Research in support of this hypothesis comes from both cross-sectional as well as longitudinal studies of children's mathematics development throughout the elementary school years.

Alloway et al. (2005) suggest that by first grade, phonological awareness is not associated with mathematics competency (i.e., being able to identify, count, add, and subtract numbers between 1 and ten, being able to identify similarities between objects and patterns, and have some knowledge of time sequences and currency) at the time of school entry.

The quality of preschool and Kindergarten phonological representations appears to be linked to individual differences in children's ability to accurately and fluently perform calculations well into the middle elementary grades (Barnes et al., 2014). In a longitudinal study, Barnes and colleagues (2014) tested whether phonological awareness (sound matching, elision) assessed between 36 and 60 months of age mediated differences in numeracy outcomes (calculation, calculation fluency, numerical reasoning, and knowledge) at 8.5 and 9.5 years of age. Study findings showed that phonological awareness at three and five years of age is a statistically significant predictor of all three measures of numeracy. Phonological awareness has also been shown to mediate the influence of measures of the executive component of the working memory system on early numeracy skills in children between the ages of five and six (Michalczyk et al., 2013).

Krajewski and Schneider (2009) propose that children start by acquiring basic conceptual knowledge, such as quantity discrimination, and then children begin to gradually develop quantity-number concepts, and then begin to understand relations between these quantity-number concepts. They propose, "because phonological awareness reflects the ability to differentiate between meaningful segments of the language and to manipulate them, it should facilitate the differentiation and manipulation of single words in the number word sequence" (Krajewski & Schneider, 2009, p. 520). Evidence in support of this claim is found in a study that shows that phonological awareness assessed in Kindergarten predicts children's basic conceptual knowledge which in turn predicts their later mathematics achievement (computation, applied mathematics, geometry) in third grade (Krajewski & Schneider, 2009).

Other longitudinal studies have also shown a correlation between early phonological awareness and later mathematical knowledge and performance in the areas of numeration and calculation in children in the early school years (Koponen et al., 2007; Krajewski & Schneider, 2009). Koponen and colleagues (2007) reported an association between phonological awareness and counting abilities in Kindergarten children. Krajewski and Schneider (2009) reported a correlation of .52 between phonological awareness and number word sequence measures in their longitudinal study following children from Kindergarten to Grade 3. Taken together these findings provide support for the idea that the phonological loop plays an important role in children's early numeracy. However, the studies in this body of research did not include measures of processing speed. This is an oversight because phonological awareness and processing speed are related constructs associated with the phonological loop. Phonological awareness may mediate the influence of processing speed on children's early numeracy and mathematics word-problem solving.

Preliminary support for this view comes from a cross-sectional study of third graders' numeracy and mathematics word-problem solving. Fuchs et al. (2006) report that phonological decoding and processing speed predicted addition and subtraction of single-digit and double-digit numbers but not word-problem solving ability. In this research measures typically used to estimate processing in the central executive component of the working memory system contributed unique variance to the prediction of mathematics word-problem solving but not to numeracy outcomes.

Other studies have shown the importance of phonological awareness on mathematics achievement persists beyond the early elementary school years (Hecht et al., 2001; Vukovic & Lesaux, 2013). Moreover, as children get older their reliance on phonologically coded information to perform more complex calculations increases (de Smedt et al., 2009; Hecht et al., 2001; Simmons, Singleton, & Horne, 2008). For instance, in a longitudinal correlational study, Hecht and colleagues (2001) examined the relations between phonological processing and mathematical computation skills. Participating children were assessed annually from second to fifth grade on mathematical computation (single-digit addition and subtraction, multi-digit addition, multiplication, and division; addition and subtraction of fractions and an algebraic equation with one unknown term; speed and accuracy with which mathematical problems are answered), phonological memory, and rate of access to phonological codes in long-term memory, and phonological awareness. Study findings showed that individual differences in phonological memory, articulation speed, and phonological awareness explained mathematical computation growth from second to fifth grade. When growth in mathematical skills was considered from year to year, phonological processing abilities, phonological memory, and articulation speed were associated with second- to third grade mathematical computation growth. From third to fourth-grade and from fourth to fifth-grade, phonological awareness alone was a significant predictor of mathematical computation growth.

In summary when findings from studies of the central executive and phonological loop are taken together they suggest that the phonological loop and the central executive components of Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory seem to be strong predictors of early numeracy and mathematics word-problem solving from the first grade onward (de Smedt et al., 2009; Meyer et al., 2010; Noël, 2009; Rasmussen & Bisanz, 2005; Swanson, 2011).

Among the few longitudinal studies that consider the simultaneous influence of the central executive and phonological loop in Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory, de Smedt et al. (2009) found measures of the phonological loop and central executive administered at the beginning of first grade predicted performance on a composite measure of general mathematics achievement including number knowledge, understanding of operations, simple arithmetic, word problems, and measurement administered four months later and at the beginning of grade two. The central executive component explained unique variance in first and second grade general mathematics achievement; the phonological loop component explained only unique variance in second but not first grade mathematics achievement. However, when the influence of prior mathematical ability was controlled for, only the phonological loop remained a unique predictor of second grade general mathematics achievement.

Rasmussen and Bisanz (2005) investigated the changes in mental representation and processing when children in Kindergarten and first grade solve spoken word problems. One set of problems included objects that could be manipulated physically and used as prompts to solve the problem. The other set of problems were presented aurally without the use of visual prompts. For Kindergarten children, measures of the central executive uniquely predicted performance on problems where no visual prompts were available. For first grade children, measures of the central executive and phonological loop together predicted performance on the same problems. Rasmussen and Bisanz (2005) suggest that Kindergarten children rely on mental models constructed from the visual prompts, and construction of these mental models from the spoken word problem inflicts a load on the central executive component. On the other hand, first graders also draw upon the phonological loop as they use inner speech to solve the problems.

A recent longitudinal study across the school years found that the central executive component and visual-spatial sketchpad predict achievement growth in mathematics from first to fifth grade (Geary, 2011). Study findings showed that working memory, processing speed, quantitative knowledge, and arithmetic competencies in first grade contribute independently to individual differences in mathematics achievement through Grade 5 beyond the contribution of general intelligence. Mathematics achievement was assessed with the Numerical Operations subtest (number discrimination, rote counting, number production, addition and subtraction, multiplication and division, and rational number problems) from the Wechsler Individual Achievement Test–II (Wechsler, 2001). The executive component was linked with more complex numerical operations tasks and its importance diminished as tasks become automatized and more dependent on long-term memory processes.

1.3.3. Relations between the Working Memory System and Later Mathematics Achievement

Gathering insights about the relations between an emerging working memory system and early numeracy and mathematics word-problem solving is an important endeavour to help explain these relations in older children, including children with mathematical learning disabilities. A number of sources have shown that working memory system accounts for individual variability in performance of older children in the upper elementary grades on mathematics outcomes (Andersson & Lyxell, 2007; Passolunghi & Siegel, 2004; Swanson et al., 2008; Swanson & Beebe-Frankenberger, 2004; Zheng et al., 2011). For example, Zheng and colleagues (2011) used structural regression models to test the contribution of the three working memory components in Baddeley's original model to mathematical word problem solving in children between the ages of eight and ten. Study findings revealed that measures of the central executive, phonological loop, and visual-spatial sketchpad significantly predicted mathematics problem solving accuracy, The magnitude of the beta weights obtained in the analyses indicated moderate effect sizes for the phonological loop and visual-spatial sketchpad and a high effect size for the central executive component.

Further evidence about the roles of the different working memory components also comes from studies comparing mathematics outcomes of older children who are typically developing and children with learning disabilities. Children with mathematical disabilities have been shown to have generalized and persistent constraints in working memory capacity (e.g. Andersson & Lyxell, 2007; Passolunghi & Siegel, 2004; Swanson et al., 2008; Swanson & Beebe-Frankenberger, 2004). For example, Passolunghi and Siegel (2004) found that children with mathematical disabilities show impairment and lower recall in all complex working memory tasks involving verbal or numerical information when compared to peers. Likewise, Swanson and Sachse-Lee (2001) emphasize that the executive processing component predicts mathematics word problem solving, independent of the contribution of short-term memory in a sample of 11-year old children with learning disabilities when compared to chronologically age-matched and younger comprehension/mathematics computation achievement-matched peers.

1.4. Summary

In general, findings from the previously discussed research on samples of children in first grade onward demonstrate that processing affiliated with the phonological loop plays an important role in numeracy skills, while the central executive component contributes to improvements in mathematics word-problem solving abilities. There is a need to determine whether the findings cited above can be extended to children in Kindergarten. That is, the central issue that remains unresolved is whether the working memory system available to children in Kindergarten is also predictive of early numeracy and mathematics word-problem solving development over the course of the first and second grade.

A second issue that arises from discussion of this research concerns whether articulation speed and phonological awareness in the phonological loop independently or together contribute to children's mathematics achievement in the primary grades. According to one view, phonological awareness and articulation speed are influenced by the stability of phonological representations in long-term memory and therefore have a strong association with each other and to mathematics achievement. From this perspective, articulation speed is faster among children who have better phonological awareness of these phonological representations.

An alternative view is that phonological awareness and articulation speed are overlapping but independent constructs and therefore may predict different aspects of mathematics achievement over time. It seems reasonable to assume that the complexity of children's phonological and computational abilities increases as they grow older and experience more advanced mathematics curricula. If this is the case, phonological awareness measured in Kindergarten is likely to be a better predictor of first grade, compared to second grade computational abilities.

A second alternative proposes that articulation speed and phonological awareness are independent constructs. Articulation speed is more a measure of general processing speed regardless of the type of information processed. Evidence in support of this view would include a different pattern of associations between each measure of processing in the phonological loop and mathematics achievement.

A related third issue is whether processing in the phonological loop influences mathematics achievement independently of the contribution of the central executive. Even though research has demonstrated that the phonological loop is an important predictor of mathematics achievement in elementary grades (e.g. de Smedt et al., 2009; Hecht et al., 2001; Meyer et al., 2010), it remains unclear whether individual differences in phonological awareness and articulation speed in Kindergarten children are more predictive of later mathematics achievement than the central executive component of the working memory system. With respect to phonological awareness, it is also important to consider that children start developing phonological awareness in preschool (e.g. Storch & Whitehurst, 2002). This is why it is also crucial to examine if children who have better phonological sensitivity skills early on in their development are also better equipped to learn the new language of mathematics once they enter school. Further, there has been a lack of consideration for acknowledging the contributory role articulation speed plays in the cognitive processes involved in mathematical competence. Previous research has demonstrated that processing speed contributes significant variance to mathematical competence in older children (Berg, 2008), and studies into whether the same pattern of relationships will be found in Kindergarten children are also needed.

The majority of the studies investigating the associations between the working memory system and mathematics achievement are cross-sectional. De Smedt et al. (2009) call for more longitudinal studies to investigate the different contribution of components within the working memory system on the prediction of mathematics achievement in the early years. Meyer et al. (2010) argue that longitudinal samples are required to address the issue if poor performance on measures of the central executive and phonological capacity influences children's mathematics skills over time. Also, Georgiou et al. (2013) point out that studies are needed to examine the relationship between processing speed and mathematics over longer developmental periods. Kyttälä, Aunio, Lepola, and Hautamäki (2014) propose that future longitudinal studies should test findings from earlier cross-sectional research because the "development of skills and cognitive components in young children may be more complex than our cross-sectional model suggests" (p. 691).

1.5. General Purpose

The present study is designed to explore the relationship between working memory and mathematics achievement by following typically developing children from Kindergarten to Grade 2. It focuses on the constraints in the central executive component of working memory at a general processing level and on the constraints in the phonological loop component of working memory when investigating the association between working memory and mathematics achievement. It also addresses some of the gaps in the literature by employing a longitudinal design, including a sample from the time children start school, and examining the contributory roles of phonological awareness and processing speed in further explaining the variance that is not explained by working memory in early mathematical skills.

1.6. Research Questions and Hypotheses

The current study addresses the primary research question: Does the central executive and/or the phonological loop within Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory account for the predictive relations between children's working memory capacity in Kindergarten and their mathematics achievement in first and second grade?

The central executive and the phonological loop components of the working memory system in Kindergarten are expected to be unique predictors of early numeracy and mathematics word-problem solving in both the first and the second grade. However, the pattern of associations is expected to differ between the phonological loop and the central executive.

The phonological loop component of the working memory system in Kindergarten children is expected to be a unique predictor of early numeracy in first and second grade. Poorly specified phonological representations are linked with poor phonological loop functioning and slow rate of access to phonological codes, which impact the ability to rapidly retrieve number facts and counting speed (Robinson, Menchetti, & Torgesen, 2002; Simmons & Singleton, 2008). If individual differences in mathematics achievement and working memory are moderated by processing in the phonological loop, the relationship between mathematics achievement and working memory will be weakened when measures of the phonological system (e.g. phonological awareness, processing speed) are partialed from the analysis.

Previous research has shown that children rely on internal verbal strategies when computing calculations (Rasmussen & Bisanz, 2005). Performance on measures of the phonological loop is also expected to predict children's mathematics word problem solving in second grade. The nature of the relationship between phonological awareness and articulation speed as estimates of processing in the phonological loop will also be explored. Since mathematical word problems are presented in a spoken form for children of this age, the phonological system is likely involved in the decoding and comprehension of the spoken language. Therefore it is expected that a portion of the variance in children's mathematical word problem solving will be explained by their performance on measures of the phonological loop.

The central executive is also expected to predict common as well as unique variance in children's early numeracy, mathematics word problem solving, and knowledge of mathematical concepts. Young children's use of decomposition strategies to compute calculations (e.g., Lemaire, Barrett, Fayol, Abdi, 1994) suggests a strong involvement of the central executive component when performing complex multi-step computations. Solving mathematical word problems also likely demands cognitive resources affiliated with the central executive to comprehend and build a problem model, and to construct a number expression, before a problem is solved. Construction and retrieval of knowledge about mathematical concepts from long-term memory is resource demanding, therefore, it is expected that performance on measures of the central executive component of the working memory system in Kindergarten children will be a unique predictor of mathematical concepts in second grade.

Chapter 2.

Method

2.1. Study Design

A longitudinal study “involves the repeated measurement of a sample of individuals, usually at the same age at the start of the study, over a period of time” (Schmidt & Teti, 2004, p. 3) in order to study associations between age changes and specific outcome behaviour changes in the sample. Longitudinal research allows for the adequate and effective investigation of individuals’ development (Magnusson, Bergman, Rudinger, & Torestad, 1991) by focusing on developmental progression, intraindividual, social, and environmental change (Schmidt & Teti, 2004). In longitudinal research, there are four research designs, according to how the sample to be studied at different time points is selected: trend studies, cohort studies, panel studies, and cross-sectional design (Gall, Gall, & Borg, 2007). The current research is a panel study and it follows the same individuals over time. This design was chosen because it is sensitive to small changes in the sample and also has “the advantage of identifying who is changing and in what way” (Gall et al., 2007, p. 305). Correlational research designs are valuable and necessary in that they allow us to determine to what degree different variables are related, however correlational research does not indicate causal relationships (Creswell, 2008). Gall et al. reason that correlational research is highly useful in social sciences because it enables researchers to analyze relationships among a large number of variables and how these variables, alone or in combination, relate to patterns of behaviour. Correlational research design was chosen for the purposes of this study because it permits the prediction of performance on one variable from performance on other variables. More specifically, this research examines which components of a working memory system accessed by Kindergarten children best predicts their mathematic ability in first and second grade. To construct the model, hierarchical linear regression analyses were performed, using mathematics ability measures (mathematics calculation, mathematics fluency, mathematics quantitative concepts, and mathematics applied problems) as dependent variables. The independent variables were the three working memory measures (Story

Retelling, Visual Matrix, and Spatial Organization), phonological awareness, and articulation speed.

2.2. Recruitment of Participants

This study employs secondary use of data. Dr. Hoskyn carried out the primary research in 2003-2007. The research was financially supported by a standard research grant from the Social Sciences and Humanities Research Council of Canada awarded in 2003 (Project Title: Working memory development for children at risk for writing disabilities).

Ethical clearance to conduct this study was provided by the Research Ethics Board of Simon Fraser University. Participants were recruited from preschools in Burnaby, Coquitlam, North Vancouver, Vancouver, Port Coquitlam, Port Moody, and West Vancouver in the Lower Mainland of British Columbia. Information sheets outlining the aims and scope of the study were sent to preschool managers and asking them for study participation.

Following approval from the preschool managers for study participation, information sheets and consent letters requesting parental permission for a child's study participation were sent home with each child at each site with the assistance of the preschool manager or preschool staff. These forms asked parents/guardians to consent to have their child participate in the study. Once letters of informed consent were sent back by the parents, they were picked up from the preschools and parents were contacted for permission to test their child at the respective preschool. Verbal assent was also obtained from children who were permitted by their parents to participate in the study. On the day each child was to begin testing, each child was informed about the purpose and structure of the activities that she or he was required to perform. Children were also informed that it is okay if they do not want to complete a task and that they could withdraw at any time before or during the completion of any activity. Before participating children started Kindergarten, school districts also granted permission for the study to be conducted.

2.3. Participants

The sample was selected from a longitudinal study focusing on working memory and writing in children. Children selected for study participation were those who had complete data on all working memory measures and at least three mathematics achievement measures. The final sample included 92 children (55 boys and 37 girls, mean age = 5 years, 7 months; range: 4 years, 4 months to 6 years, 5 months at the start of testing) who attended 53 schools within six school districts of the Lower Mainland in British Columbia.

The schools were situated in neighbourhoods that according to analysis conducted by the Human Early Learning Partnership reflected a range of vulnerabilities as measured by the Early Development Instrument (EDI). The EDI is a population tool designed to measure children's school readiness (Janus et al., 2007) in five core areas of child development: (a) physical health and well-being, (b) social competence, (c) emotional maturity, (d) language and cognitive development, and (e) communication skills and general knowledge. Kindergarten teachers completed the questionnaire for individual children and results were grouped at neighbourhood, regional, and provincial levels in order to assess the population school readiness. According to Hymel, LeMare and McKee (2011), overall EDI scores are significantly correlated with standardized measures of school readiness, child-based indices of early social competence, and phonological awareness. As shown in Table 2.1, 9.8% (n = 9) of children in the sample attended schools in neighbourhoods where vulnerability on the EDI Physical Health and Well-Being Scale was above BC norms; 7.6% (n = 7) of children in the sample attended schools in neighbourhoods where vulnerability on the EDI Social Competence Scale was above BC norms; 17.39% (n = 16) of children in the sample attended schools in neighbourhoods where vulnerability on the EDI Emotional Maturity Scale was above BC norms; 19.57% (n = 18) of children in the sample attended schools in neighbourhoods where vulnerability on the EDI Language and Cognitive Scale was above BC norms; and 23.91% (n = 22) of children in the sample attended schools in neighbourhoods where vulnerability on the EDI Communication Skills Scale was above BC norms. Table 2.2 shows the vulnerability in the EDI five core areas for all participating in the study school districts. The Vancouver School District was vulnerable on physical health and well-being in comparison to BC norms. The Vancouver School District, New Westminster School District and the Burnaby

School District were vulnerable on social competence and communications skills in comparison to BC norms. The Vancouver School District, New Westminster School District, and the North Vancouver School District were vulnerable on emotional maturity in comparison to BC norms. The Burnaby School District was vulnerable on language and cognitive development in comparison to BC norms.

Table 2.1. **Study participants' physical, social, emotional, language, and communication vulnerability based on school district**

School District	Area	Sample Schools (n)	Sample Participants (n)	EDI Participants (n)	EDI Physical Vulnerability %	EDI Social Vulnerability %	EDI Emotional Vulnerability %	EDI Language Vulnerability %	EDI Communication Vulnerability %
SD 39	Grandview - Woodlands	1	1	154	16	20	18	14	20
SD 40	Connaught Heights	1	1	54	9	19	15	11	19
	Queens Park	1	1	105	7	7	10	3	10
SD 41	Burnaby Lake	1	1	117	9	14	8	9	22
	Deer Lake	2	2	131	11	13	13	15	13
	Duthie - Government	1	1	141	10	16	16	14	16
	Metrotown	1	2	148	6	15	12	19	30
	South East Burnaby	1	1	229					
SD 43	Burquitlam	1	1	138	10	9	10	12	20
	Citadel Heights	3	3	105	2	4	8	5	5
	Como Lake	2	5	120	7	13	10	5	13
	Coquitlam River	3	7	141	15	13	9	16	21
	Eagleridge	1	2	136	6	7	10	5	14
	Hillcrest	2	4	149	1	5	9	7	13
	Inlet	2	2	300	4	5	8	4	5
	Maillardville	1	3	111	12	11	8	13	17
	Town Centre	1	1	154	6	8	8	11	19

(table continues)

School District	Area	Sample Schools (n)	Sample Participants (n)	EDI Participants (n)	EDI Physical Vulnerability %	EDI Social Vulnerability %	EDI Emotional Vulnerability %	EDI Language Vulnerability %	EDI Communication Vulnerability %
SD 44	Deep Cove - Dollarton	4	11	88	7	1	7	6	10
	Delbrook - Upper Lonsdale	2	3	75	7	13	7	4	1
	Grand Boulevard - Moodyville	3	6	135	1	7	8	5	7
	Lonsdale	1	1	141	14	18	18	16	26
	Lynn Valley	2	2	133	8	11	10	6	7
	Lynnmour/Blueridge	2	3	139	9	11	14	11	11
	Norgate/Pemberton	1	1	124	11	14	15	10	17
	Upper Capilano - Edgemont	2	4	160	6	9	8	3	4
	Westlynn	2	4	76	7	11	15	9	7
SD 45	Ambleside - Dundarave	6	14	115	7	4	5	1	4
	British Properties	2	3	58	5	10	2	6	10
	Caulfield - West Bay	1	2	64	3	8	5	5	2
	Provincial Vulnerability Rate				12	13.3	11.9	11.3	14.2

Note. SD 39 = Vancouver School District; SD 40 = New Westminster School District; SD 41 = Burnaby School District; SD 43 = Coquitlam School District; SD 44 = North Vancouver School District; SD 45 = West Vancouver School District.

Physical = Physical Health and Well-Being; Social = Social Competence; Emotional = Emotional Maturity; Language = Language and Cognitive Development; Communication = Communication Skills. The data for all school districts except SD 44 is based on Wave 2 (2004 – 2007) data from the Early Development Instrument (EDI), Human Early Learning Partnership (HELP). The data for SD 44 is based on Wave 3 (2007 – 2009) data from EDI because Wave 2 data is not available.

Table 2.2. School districts' physical, social, emotional, language, and communication vulnerability rate

School District	EDI Physical Vulnerability %	EDI Social Vulnerability %	EDI Emotional Vulnerability %	EDI Language Vulnerability %	EDI Communication Vulnerability %
SD 39 Vancouver School District	14	16	14	10	23
SD 40 New Westminster School District	9	14	13	10	16
SD 41 Burnaby School District	10	14	11	15	21
SD 43 Coquitlam School District	7	8	8	7	13
SD 44 North Vancouver School District	8	11	12	8	10
SD 45 West Vancouver School District	6	6	7	2	5
Provincial Vulnerability Rate	12	13.3	11.9	11.3	14.2

Note. The data for all school districts except SD 44 is based on Wave 2 (2004 – 2007) data from the Early Development Instrument (EDI), Human Early Learning Partnership (HELP). The data for SD 44 is based on Wave 3 (2007 – 2009) data from EDI because Wave 2 data is not available.

All children in the study were Canadian-born and primarily spoke English as their first language (97.8%). Of all parents, 86% reported English being their language of cultural origin. Maternal education levels ranged from high-school to doctoral degrees, with the majority of mothers having Bachelor's degrees (44.44%). Paternal education levels ranged from some high school to doctoral degrees, with the majority of fathers having Bachelor's degrees (32.4%). Demographics information is presented in Table 2.3.

Table 2.3. Demographics information of participants

Characteristic	n	%
Sex		
Male	55	59.8%
Female	37	40.2%
Children's English Language Proficiency		
Speaks English as 1st language	90	97.8%
Speaks English as additional language	2	2.17%
Children's Second Language Proficiency		
Speaks second language	16	17.39%
Does not speak second language	76	82.61%
Parental English Language Proficiency		
Speaks English as 1st language	79	86%
Speaks English as additional language	13	14.13%
Maternal Level of Education		
Some high school	-	-
High school	9	10%
Some College	27	30%
University Degree		
Bachelor's	40	44.4%
Master's or a Professional degree	12	13.3%
Doctoral	2	2.2%
Paternal Level of Education		
Some high school	2	1.8%
High school	16	14.4%
Some College	23	20.7%
University Degree		
Bachelor's	36	32.4%
Master's or a Professional degree	10	9%
Doctoral	3	2.7%

Note. Four parents (two mothers and two fathers) did not report their level of education.

2.4. Procedures

A statistical power analysis was performed for sample size estimation, based on data from a meta-analytical study on shifting ability and mathematical performance in children by Yeniad, Malda, Mesman, van IJzendoorn, and Pieper (2013) .The effect size

(ES) in this study was 0.54 (r = 0.26) considered to be moderate using Cohen's (1988) criteria. With an alpha = .05 and power ($1-\beta$) = 0.95, the projected sample size needed with this effect size (GPower 3.0.5, Faul, Erdfelder, Lang, & Buchner, 2007) is approximately N = 32. Thus, a sample size of 92 is more than adequate for the main objectives of this study.

An extensive battery of tests was individually administered to participating children over two 45-minute sessions in preschool and over two 60-minute sessions in Kindergarten, Grade 1, and Grade 2 on separate days to assess working memory, phonological awareness, processing speed, and mathematics achievement. The testing took place either at the children's Kindergartens, elementary schools, or in the children's homes and was administered by graduate students trained in test administration. Test administration was counterbalanced to control for order effects. Children were allowed short breaks during testing to ensure that they were focused and on task.

2.5. Measures

The battery of individually administered experimental and standardized tasks is described below. Children completed two test batteries. The first test battery measured vocabulary, working memory, and phonological processing. The second test battery was administered to measure children's academic achievement in mathematics. Table 2.4 shows when each measure was administered.

Table 2.4. Constructs, measures, and timing of administration

Construct	Measure	Administered		
		K	Grade 1	Grade 2
IQ				
Vocabulary	Stanford-Binet V Verbal Reasoning	X		
Working Memory	Working Memory			
Central Executive	Story Retelling	X		
	Visual Matrix	X		
	Spatial Organization	X		
Phonological Processing				
Phonological Deletion	CTOPP Elision	X		
Articulation Speed	Articulation Speed	X		
Mathematics Outcomes				
General Computation	Woodcock-Johnson III Calculation		X	X
Computation Fluency	Woodcock-Johnson III Math Fluency		X	X
Mathematical Concepts	Woodcock-Johnson III Quantitative Concepts			X
Word Problems	Woodcock-Johnson III Applied Problems			X

2.5.1. Vocabulary

Participants were administered the Vocabulary subtest from Stanford-Binet Test of Intelligence—Fifth Edition (Thorndike, Hagen, & Sattler, 1986, which measures verbal reasoning. For this task, the child is required to verbally define isolated words by providing a definition or synonym of the stimulus word (e.g., "What is a puddle?"). Scores range between 0 and 2 depending on the accuracy of response according to norm-referenced scoring guidelines in the manual. The test is the most highly correlated subtest with overall verbal IQ (Sattler, 1988). The test has an internal consistency reliability coefficient of .96 according to the test manual.

2.5.2. Working Memory

One verbal and two visual-spatial working memory measures were administered to assess working memory capacity and processing efficiency. The working memory battery is based on measures of adult working memory capacity originally created by Swanson (Swanson Cognitive Processing Test, 1996) and later modified and adapted by Dr. Maureen Hoskyn to assess children. The measures involve processing (i.e., asking children questions about content that is to be remembered) and storage of information (i.e., accuracy of item retrieval). Verbal working memory was assessed with the Story Retelling task. Visual-spatial working memory was assessed with the Visual Matrix and Spatial Organization tasks. During administration of the working memory battery, the Story Retelling was administered first, followed by Visual Matrix and Spatial Organization.

Story retelling. This task requires the child to reproduce from memory a short story about a giraffe in a correct sequence. The story has nine sentences, ranging from one to 12 words in length and forming 12 main clauses. The child is instructed to listen carefully to the story presented by the test administrator with the help of a puppet. A process question acting as a distractor for item recall and requiring a yes/no response is asked upon conclusion of the story. Then, the child is given the puppet and instructed that is his or her time to retell the story. After the test administrator praises the child for her or his good story telling abilities, the child is told the story details that were left out and prompted to retell the story one more time. Upon administration of the remaining working memory tasks in the testing battery, the child is asked to tell the story one more time without any a priori modeling. The task is scored based on the sequence and number of propositions accurately recalled by the child at three time points: before initial prompting, after prompting, and at maintenance. Each correctly recalled proposition in relation to the remaining story propositions is awarded a score of 1. The sample Cronbach's alpha coefficients for initial, gain, and maintenance scores were .85, .84, and .84.

Visual matrix. The purpose of this task is to assess children's ability to remember visual sequences within a matrix. Children are presented with plastic chips arranged in a matrix on white paper and asked to observe the test administrator tapping the chips, answer a question, and then tap the same chips that are tapped by the examiner. A process question acting as a distractor for item recall and requiring a yes/no response is asked after each item within a set is presented. The task difficulty ranges from a matrix with four squares and two chips to a matrix of 21 squares and seven chips. If the child misses out tapping a chip, taps additional chips, or taps chips in incorrect sequence, the test administrator prompts the child by telling him or her that she or he has missed out a particular chip and asks the child to repeat taping the chips again. The administration of the task continues until the child is unable to correctly answer the process question for a matrix or is unable to correctly perform the task with prompting. Upon administration of the remaining working memory tasks in the testing battery, the child is administered the highest item that he/she performed correctly without any probing. If the child is able to accurately tap the chips in the correct sequence, the highest gain score is assigned for the task; and if the child fails the task, the initial score is assigned. The task is scored at three time points: before initial prompting, after prompting, and at maintenance. Each correctly recalled matrix is awarded a score of 1. The sample Cronbach's alpha coefficients for initial, gain, and maintenance scores were .85.

Spatial organization. This task requires the child to memorize the positioning of different small toys within an array. The task difficulty ranges from an array with one toy to an array with seven toys, for a total of eight arrays. Before the administration of the task, small toys are taken one by one from a bag and positioned slightly out of child's reach. A white sheet of paper with circles arranged in a diagram form is placed in front of the child. The child is instructed that she or he is going to play a game after the test administrator arranges the toys on different spots on the paper. The child is asked to look at the toys and to remember exactly where they are positioned. Then, the child is asked to look away, while the test administrator clears all the toys from the array. A process question acting as a distractor for item recall and requiring a yes/no response is asked after each array is presented. The child is given all the toys including one new distractor toy and instructed to put the toys in their spots and give to the test administrator any extra toys that do not belong in the array. After child's first attempt at arranging the toys, the child is praised for his or her gaming abilities. If the child has made a mistake, the child is prompted of what the correct organization of the toys should be and asked to place the toys in their correct spots again. The administration of the task continues until the child is unable to correctly answer the process question for an array or is unable to correctly perform the task with prompting. Upon administration of the remaining working memory tasks in the testing battery, the child is administered the highest item that she or he performed correctly without any probing. If the child is able to accurately position the toys in the array, the highest gain score is assigned for the task; and if the child fails the task, the initial score is assigned. The task is scored at three time points: before initial prompting, after prompting, and at maintenance. Each correctly recalled array is assigned one point. The sample Cronbach's alpha coefficients for initial, gain, and maintenance scores were .85.

2.5.3. Phonological Processing

Phonological deletion. The Elision subtest from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) was administered. This test measures the extent to which a child can pronounce and manipulate the sounds of a word. For example, the child is instructed: "Say cat." After repeating "cat", the child is told: "Now say cat without saying /c/." The test has a reliability coefficient of .80, according to the testing manual.

Articulation speed. This task required children to name five times as quickly as possible five two-syllable words (e.g., "scissors," "giraffe," "hammer"), The test administrator used a stopwatch to time participants and children's responses were also digitally recorded to obtain the time taken to name the array of words to the nearest one-hundredth of a second. The sample Cronbach's alpha coefficient for articulation speed was .76.

2.5.4. Mathematic Ability

General computation. The Calculation subtest of the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock, McGrew & Mather, 2007) measures a child's ability to perform paper and pencil mathematic computations. The items on the test range in increasing difficulty from number writing through performing numerical operations (e.g. addition, subtraction, multiplication, division) and are presented in either horizontal or vertical format. The publisher reports reliability between .80 and .87. The dependent variable will be the summed score of all correct responses of the test.

Computation fluency. The Math Fluency subtest of the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock et al., 2007) measures a child's ability to solve simple addition, subtraction, and multiplication problems quickly. Children are given a time limit of three minutes and instructed to complete as many simple single-digit mathematic problems and skipping the ones they do not know. The test has a reliability coefficient between .90 and .93, according to the testing manual. Total number of correct responses achieved within the time limit will be the dependent variable.

Word problems. The Applied Problems subtest of the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock et al., 2007) measures a child's ability to solve relatively simple numerical and spatial problems. The examiner reads the problems aloud (e.g., "If Diana saved a nickel each day for one week, how much money would she have at the end of that week?"). Items on the test start with simple counting questions, then story problems with pictures, and finally story problems without pictures. The test has a reliability coefficient between .91 and .93, according to the manual. The dependent variable will be the summed score of all correct responses of the test.

Mathematical concepts. The Quantitative Concepts subtest of the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock et al., 2007) measures the child's knowledge and understanding of mathematical concepts, symbols, vocabulary, and number patterns. This test consists of two subtests: Concepts and Number Series. For the Concepts subtest, children are asked to count and identify numbers, shapes, and sequences and to know mathematical terms and formulas (e.g., rounding numbers). The 34 items on this subtest range in increasing difficulty. For the Number Series subtest, children are required to figure out a pattern in series of numbers and then provide the missing number in the series. The 23 problems on this subtest range in increasing difficulty. According to the publisher, the average internal reliability for the Quantitative Concepts subtest is high (r = .91). The sum of the correct responses for the Concepts subtest and the Number Series subtest will be the dependent variable.

2.6. Data Analysis

The data set was checked for missing values, skewness, and kurtosis for each of the variables, linearity, and homoscedasticity. The minimum and maximum values, means, standard deviations for each of the variables were inspected. Z-scores were calculated to determine if there are any univariate outliers. To test for multivariate outliers Mahalanobis distance was used.

In the first part of the analyses, descriptive statistics and zero order correlations are presented. In the second part of the analysis, after converting all raw scores to standardized *z*-scores, correlational and hierarchical regression analyses were conducted to determine the relationship between predictor variables in Kindergarten and mathematics achievement in first and in second grade.

In order to construct a model of how the phonological system and central executive system contribute to mathematics achievement, a series of hierarchical regression analyses were performed using each mathematics ability measure at Grade 1 and Grade 2 as a criterion variable. Predictor variables were Story Retelling, Visual Matrix, Spatial Organization, Elision, and Articulation Speed. Model 1 (Verbal Ability) was designed to explore the amount of variance in each mathematical outcome variable that was accounted for by Age and Vocabulary of the child at the time of assessment in Kindergarten. Model 2 (Phonological Loop) was designed to examine the individual contributions of Phonological Awareness and Articulation Speed to each mathematical outcome variable after controlling for Age and Vocabulary. Model 3 (WM Executive) and Model 4 (WM Executive) explored the amount of variance in each mathematical outcome variable that was accounted for by the working memory executive system in Kindergarten. More specifically, Model 3 was designed to examine the individual contribution of the working memory executive system to each mathematical outcome variable after controlling for Age and Vocabulary. Model 4 was designed to examine the individual contribution of the working memory executive system to each mathematical outcome variable after controlling for Age, Vocabulary, and the phonological system. Model 5 (Phonological Loop) was designed to investigate whether Phonological Awareness and Articulation Speed in Kindergarten contributed significant variance to each mathematical outcome variable after controlling for the influence of Age, Vocabulary, and the working memory executive system.

Chapter 3.

Results

The results of the study are presented in three sections. First, descriptive statistics are reported. Second, zero-order correlations among the study variables are described. Third, results of hierarchical regression analyses are presented. Each model in these analyses explains the relative contributions of working memory executive (Verbal Working Memory, Visual Working Memory) and phonological loop (Articulation Speed, Phonological Awareness) in Kindergarten to the prediction of mathematics achievement in Grades 1 and 2.

Prior to analysis, normality of the data was considered by examining the distribution of scores on each measure via statistical (skewness, kurtosis) and graphical (histograms and Q-Q plots) methods. This examination revealed that all variables were normally distributed except for Articulation Speed, which was positively skewed. On this variable, a logarithmic transformation was performed to normalize the distribution. Transformed scores on Articulation Speed were used in further analyses. All measures met standard criteria for univariate normality, with skewness and kurtosis within the range of ±3. Multivariate outliers were examined by calculating Mahalanobis's d^2 with the use of a $p < .001$ criterion. None of the cases were deemed multivariate outliers. Homoscedasticity was examined via scatterplots of the standardized residuals against each of the dependent variables and these indicated reasonable consistency of spread through the distributions. Tests to determine if the data met the collinearity assumption indicated that multicollinearity was unlikely to be a concern (Vocabulary, Tolerance = .84, *VIF* = 1.20; Phonological Awareness, Tolerance = .88, *VIF* = 1.14; Articulation Speed, Tolerance = .91, *VIF* = 1.11; Story Retelling, Tolerance = .81, *VIF* = 1.23; Visual Matrix, Tolerance = .62, *VIF* = 1.62; Spatial Organization, Tolerance = .66, *VIF* = 1.52). The data were also inspected for multicollinearity by examining first-order correlations among measures. Moderate intercorrelation (.51) was found between the scores on the Visual Matrix and Spatial Organization tasks.

With the exception of mathematics achievement in second grade, missing data ranged from 4% to 10% for all variables. The high percentage of missing data for the two second grade mathematics variables (25% & 33%) was due to errors in administration. All missing values within a variable were replaced with the mean of that variable, based on all valid cases in the sample. Although a major drawback when using mean substitution procedure is narrowing of the variance leading to distortion of the variable's distribution of values (Tabachnick & Fidell, 2007), this technique was chosen in order to preserve the sample size.

The means, standard deviations, and ranges for all variables are displayed in Table 3.1. The table shows that the data were normally distributed without ceiling or floor effects. Scaled scores were calculated using age norms provided in technical manuals for the Stanford-Binet Test of Intelligence—Fifth Edition (Thorndike et al., 1986), the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) and the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock et al., 2007)

Table 3.1. Sample characteristics

Variable	M	SD	Minimum - Maximum
Kindergarten			
Chronological Age (in months)	67.50	6.14	52-89
Vocabulary			
Raw score	16.10	2.69	11-22
Standard score	53.71	7.36	33-71
Working Memory Executive			
Story Retelling	7.83	2.71	1-12
Visual Matrix	3.18	1.33	0-5
Spatial Organization	3.62	1.50	0-6
Phonological Loop			
Articulation Speed	40.32	17.94	18.50-109
Phonological Awareness			
Raw score	10.80	4.03	0-16
Standard score	14.12	2.33	7-18
Grade 1			
Calculation			
Raw score	6.84	2.72	1-13
Standard score	105.51	13.08	75-131
Math Fluency			
Raw score	19.08	10.35	1-39
Standard score	100.15	11.93	69-123
Grade 2			
Calculation			
Raw score	9.62	2.81	4-16
Standard score	102.04	11.66	72-122
Math Fluency			
Raw score	31.53	12.83	7-68
Standard score	99.50	13.65	70-135
Applied Problems			
Raw score	28.34	4.93	18-42
Standard score	107.45	16.28	76-152
Quantitative Concepts	26.39	4.41	14-37

Note. All working memory executive scores, Articulation Speed and Quantitative Concepts scores are raw scores. Insufficient data did not allow calculation of standard scores for the Quantitative Concepts subtest.

3.1. Correlational Analyses

Zero-order Pearson correlation coefficients were calculated to estimate the associations among variables. As shown in Table 3.2, correlations among mathematics achievement variables ranged from .43 to .76 (all *p*'s < .01). A significant association was found between the two visual-spatial working memory measures (Visual Matrix and Spatial Organization), *r* = .51 (*p* < .01). While the correlation between Verbal Working Memory (Story Retelling) and one of the visual-spatial working memory measures (Spatial Organization) did not reach statistical significance, *r* = .22 (*p* = ns), a significant association was found between Verbal Working Memory (Story Retelling) and the other visual-spatial working memory measure (Visual Matrix), *r* = .32 (*p* < .01). The following discussion focuses on the pattern of correlations found between Kindergarten variables and each mathematics outcome variable in Grade 1 and Grade 2.

3.1.1. Early Numeracy (Calculation)

Two Kindergarten variables had a statistically detectible relationship with Calculation in first grade: Visual Working Memory (Spatial Organization), *r* = .35 (*p* < .01) and Phonological Awareness, *r* = .33 (*p* < .01). A similar pattern of correlations was found between these variables and Calculation in second grade: Visual Working Memory (Spatial Organization), *r* = .41 (*p* < .01), Phonological Awareness, *r* = .29 (*p* < .01). However, correlations between Age, Vocabulary, Verbal Working Memory, Articulation Speed and Calculation in Grade 1 and Grade 2 did not reach statistical significance.

3.1.2. Early Numeracy (Math Fluency)

The Kindergarten variables that had a statistically detectible relationship with Math Fluency in first grade were Visual Working Memory (Spatial Organization), *r* = .33 (*p* < .01) and Phonological Awareness, *r* = .30 (*p* < .01). A similar pattern of correlations was found between these Kindergarten variables and Math Fluency in the second grade: a significant association was found between Math Fluency and Visual Working Memory (Spatial Organization), *r* = .40 (*p* < .01) and Phonological Awareness, *r* = .24 (*p* < .05). The association between Chronological Age, Vocabulary, Verbal Working Memory, Articulation Speed, and Math Fluency in Grade 1 and Grade 2 did not reach statistical significance.

3.1.3. Mathematics Word Problem Solving (Applied Problems)

The Kindergarten variables that had a statistically detectible relationship with Applied Problems in second grade were Chronological Age, $r = .27$ ($p < .05$); Vocabulary, $r = .38$ ($p < .01$); Visual Working Memory (Visual Matrix, $r = .32$, $p < .05$ and Spatial Organization, $r = .37$, $p < .01$); Articulation Speed, $r = -.30$ ($p < .05$), and Phonological Awareness, $r = .39$ ($p < .01$). The association between Verbal Working Memory and Applied Problems in Grade 2 did not reach statistical significance.

3.1.4. Knowledge of Mathematical Concepts (Quantitative Concepts)

The Kindergarten variable that had a statistically detectible relationship with Quantitative Concepts in second grade was Visual Working Memory (Spatial Organization, $r = .30$, $p < .05$). The association between Chronological Age, Verbal Abilities, Verbal Working Memory, Articulation Speed, Phonological Awareness, and Quantitative Concepts in Grade 2 did not reach statistical significance.

Table 3.2. Correlations among Kindergarten variables and first- and second-grade mathematics outcome variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Chronological Age	-												
2. Vocabulary	.247*	-											
WM Executive													
3. Story Retelling	.297**	.241*	-										
4. Visual Matrix	.463**	.101	.319**	-									
5. Spatial Organization	.332**	.125	.216	.514**	-								
Phonological Loop													
6. Articulation Speed	.040	-.171	-.157	.105	-.030	-							
7. Phon. Awareness	.302**	.353**	.155	.176	.290**	-.175	-						
Math. Achievement Grade 1													
8. Calculation	.076	.150	-.056	.062	.351**	-.116	.329**	-					
9. Math Fluency	.072	.088	-.091	.060	.326**	-.124	.301**	.757**	-				
Math. Achievement Grade 2													
10. Calculation	.025	.131	-.113	.110	.405**	-.226	.268*	.556**	.644**	-			
11. Math Fluency	-.004	.118	.060	.130	.398**	-.252	.242*	.555**	.710**	.689**	-		
12. Applied Problems	.270*	.384**	.186	.316*	.374**	-.295*	.386**	.427**	.564**	.508**	.567**	-	
13. Quant. Concepts	-.133	.115	.021	-.009	.296*	-.239	.231	.556**	.563**	.541**	.531**	.467**	-

Note. *$p < .05$. **$p < .01$. WM Executive = Working Memory Executive; Math. Achievement = Mathematics Achievement; Phon. Awareness = Phonological Awareness; Quant. Concepts = WJ III Quantitative Concepts.

3.2. Regression Analyses

In order to assess the relative contribution of the central executive and phonological loop to mathematical outcomes in first and second grade, a series of regression analyses on several outcome measures from the Woodcock-Johnson III Tests of Achievement (WJ—III; Woodcock et al., 2007) were conducted. The following section reports results from these regression analyses on the outcome measures related to early numeracy (first grade Calculation and Math Fluency, second grade Calculation and Math Fluency), mathematics word problem solving (second grade Applied Problems), and knowledge of mathematical concepts (second grade Quantitative Concepts).

Prior to running the regression analyses, raw scores on Chronological Age, Vocabulary, Working Memory, Phonological Awareness, and mathematics achievement were converted to standardized *z*-scores based on the average sample variance. In a series of multiple regression analyses to assess the relative contribution of a working memory executive and the phonological loop to Calculation and Math Fluency in Grade 1 and Grade 2 and to Applied Problems and Quantitative Concepts in Grade 2, the log transformed score of Articulation Speed and the standardized *z*-scores for all remaining variables were included. Only predictor variables that had a statistically detectible association with the criterion, as described in the previous correlational analyses were included in the model. These variables were: Chronological Age, Vocabulary, Visual Matrix, Spatial Organization, Phonological Awareness, and Articulation Speed. Visual Matrix and Spatial Organization were added to the models separately, because a different pattern of correlations was found between these two variables and the mathematics achievement outcome variables. Spatial Organization correlated with all measures of mathematics achievement, with correlations ranging from .30 ($p < .05$) to .40 (for correlations > 30, $p < .01$). Visual Matrix was positively associated only with Applied Problems, $r = .32$ ($p < .05$).

In each model, all variables within a block were forced into the model simultaneously and blocks were entered sequentially in the order shown. Table 3.3 and Table 3.4 show the relative contribution of the working memory executive and the phonological loop estimated in Kindergarten to Calculation and Math Fluency in Grade 1 and Grade 2. Model 1 (Verbal Ability) describes the amount of variance in each mathematical outcome variable that was accounted for by Vocabulary and the Age of the child at the time of assessment in Kindergarten. In the remaining three models, Age and Vocabulary were added to the model as the first step of the model. Model 2 (Phonological Loop) examined the contribution of Phonological Awareness in the phonological loop to each mathematical outcome after controlling for Age and Vocabulary. While Articulation Speed is a variable that is often associated with the phonological loop, it was not included in this model because the correlation between Articulation Speed and Calculation and Math Fluency outcomes were not statistically detectible. Model 3 (WM Executive) examined the contribution of Visual Working Memory (Visual Matrix and Spatial Organization) that was entered simultaneously to the model after controlling for Age and Vocabulary. In Model 4 (WM Executive), Visual Working Memory variables (Visual Matrix and Spatial Organization) were entered to the model after controlling for Age, Vocabulary, and Phonological Awareness. In Model 5 (Phonological Loop), Phonological Awareness variables were entered to the model, after controlling for Age, Vocabulary, and Visual Working Memory (Visual Matrix and Spatial Organization).

Table 3.5 shows the relative contribution of the working memory executive and the phonological loop estimated in Kindergarten to Applied Problems and Quantitative Concepts in Grade 2. In Model 1 (Verbal Ability) the amount of variance in each mathematical outcome variable that was accounted for by Vocabulary and the Age of the child at the time of assessment in Kindergarten is described. In the remaining three models, Age and Vocabulary were added to the model as the first step of the model. In Model 2 (Phonological Loop) the contribution of Phonological Awareness and Articulation Speed in the phonological loop to each mathematical outcome is examined after controlling for Age and Vocabulary. Model 3 (WM Executive) examined the contribution of Visual Working Memory (Visual Matrix and Spatial Organization) that was entered simultaneously to the model, after controlling for Age and Vocabulary. In Model 4 (WM Executive), Visual Working Memory variables (Visual Matrix and Spatial Organization) were entered to the model after controlling for Age, Vocabulary, Phonological Awareness, and Articulation Speed. In Model 5 (Phonological Loop), Phonological Awareness and Articulation Speed variables were entered to the model after controlling for Age, Vocabulary, and Visual Working Memory (Visual Matrix and Spatial Organization).

Table 3.3. Predictive models of first grade early numeracy (Calculation and Math Fluency)

	Calculation – Grade 1					Math Fluency – Grade 1				
Model & Variable	R^2	B	SE	β	t ratio	R^2	B	SE	β	t ratio
1. Verbal Ability	.02					.01				
Age		.04	.11	.04	.40		.06	.11	.06	.51
Vocabulary		.13	.11	.14	1.25		.07	.11	.07	.67
2. Phonological Loop	.10					.08				
Age		-.03	.11	-.03	-.24		-.01	.11	-.01	-.11
Vocabulary		.05	.11	.05	.45		-.01	.11	-.01	-.10
Phonological Awareness		.31	.11	.31**	2.78		.30	.11	.30**	2.67
3. WM Executive	.15					.12				
Age		-.02	.12	-.02	-.15		-.00	.12	-.00	-.01
Vocabulary		.11	.10	.12	1.13		.05	.10	.05	.52
Visual Matrix		-.15	.13	-.15	-1.21		-.14	.13	-.14	-1.11
Spatial Organization		.42	.12	.41**	3.53		.39	.12	.38**	3.24**
4. WM Executive	.19					.16				
Age		-.06	.11	-.06	-.52		-.04	.12	-.04	-.36
Vocabulary		.05	.10	.05	.49		-.01	.10	-.01	-.09
Phonological Awareness		.24	.11	.24*	2.21		.23	.11	.23*	2.12
Visual Matrix		-.14	.12	-.14	-1.15		-.13	.13	-.13	-1.05
Spatial Organization		.37	.12	.36**	3.10		.34	.12	.33**	2.81

Note. *$p < .05$. **$p < .01$.

(table continues)

	Calculation – Grade 1					Math Fluency – Grade 1				
Model & Variable	R²	B	SE	*β*	t ratio	R²	B	SE	*β*	t ratio
5. Phonological Loop	.19					.16				
Age		-.06	.11	-.06	-.52		-.04	.12	-.04	-.36
Vocabulary		.05	.10	.05	.49		-.01	.10	-.01	-.09
Visual Matrix		-.14	.12	-.14	-1.15		-.13	.13	-.13	-1.05
Spatial Organization		.37	.12	.36**	3.10		.34	.12	.33**	2.81
Phonological Awareness		.24	.11	.24*	2.21		.23	.11	.23*	2.12

Note. *$p < .05$. **$p < .01$.

Table 3.4. Predictive models of second grade early numeracy (Calculation and Math Fluency)

	Calculation – Grade 2					Math Fluency – Grade 2				
Model & Variable	R²	B	SE	*β*	t ratio	R²	B	SE	*β*	t ratio
1. Verbal Ability	.02					.01				
Age		-.01	.11	-.01	-.06		-.03	.11	-.03	-.30
Vocabulary		.13	.11	.13	1.23		.13	.11	.13	1.17
2. Phonological Loop	.07					.06				
Age		-.07	.11	-.06	-.59		-.09	.11	-.09	-.80
Vocabulary		.06	.11	.06	.54		.06	.11	.06	.52
Phonological Awareness		.27	.12	.26*	2.31		.25	.12	.24*	2.16
3. WM Executive	.16					.17				
Age		-.11	.12	-.10	-.92		-.16	.12	-.15	-1.34
Vocabulary		.11	.10	.11	1.12		.11	.10	.11	1.07
Visual Matrix		-.08	.13	-.08	-.62		-.03	.13	-.03	-.26
Spatial Organization		.44	.12	.42***	3.67		.45	.12	.43***	3.72
4. WM Executive	.19					.19				
Age		-.14	.12	-.14	-1.19		-.19	.12	-.18	-1.58
Vocabulary		.06	.10	.06	.62		.06	.10	.06	.61
Phonological Awareness		.19	.11	.18	1.68		.17	.11	.16	1.50
Visual Matrix		-.07	.13	-.07	-.56		-.03	.13	-.03	-.21
Spatial Organization		.40	.12	.38**	3.30		.41	.12	.39**	3.37

Note. **p* < .05. ***p* < .01. ****p* < .001.

(table continues)

	Calculation – Grade 2					Math Fluency – Grade 2				
Model & Variable	*R*²	*B*	*SE*	*β*	*t* ratio	*R*²	*B*	*SE*	*β*	*t* ratio
5. Phonological Loop	.19					.19				
Age		-.14	.12	-.14	-1.19		-.19	.12	-.18	-1.58
Vocabulary		.06	.10	.06	.62		.06	.10	.06	.61
Visual Matrix		-.07	.13	-.07	-.56		-.03	.13	-.03	-.21
Spatial Organization		.40	.12	.38**	3.30		.41	.12	.39**	3.37
Phonological Awareness		.19	.11	.18	1.68		.17	.11	.16	1.50

Note. *p < .05. **p < .01. ***p < .001.

Table 3.5. Predictive models of second grade mathematics word problem solving (Applied Problems) and knowledge of mathematical concepts (Quantitative Concepts)

	Applied Problems – Grade 2					Quantitative Concepts – Grade 2				
Model & Variable	R^2	B	SE	β	t ratio	R^2	B	SE	β	t ratio
1. Verbal Ability	.13					.02				
Age		.14	.09	.16	1.56		-.10	.09	-.12	-1.11
Vocabulary		.24	.09	.28**	2.76		.09	.09	.12	1.08
2. Phonological Loop	.19					.05				
Age		.12	.09	.13	1.30		-.13	.09	-.16	-1.47
Vocabulary		.17	.09	.20	1.92		.05	.09	.06	.58
Phonological Awareness		.15	.09	.17	1.58		.15	.09	.19	1.65
Articulation Speed		- 1.00	.53	-.19	-1.90		-	-	-	-
3. WM Executive	.21					.12				
Age		.02	.10	.02	.20		-.15	.10	-.18	-1.54
Vocabulary		.23	.08	.27**	2.79		.08	.08	.10	.97
Visual Matrix		.12	.11	.13	1.10		-.09	.10	-.11	-.87
Spatial Organization		.22	.10	.24*	2.19		.30	.10	.35**	3.00
4. WM Executive	.27					.13				
Age		.01	.10	.01	.08		-.17	.10	-.20	-1.70
Vocabulary		.18	.09	.21*	2.30		.05	.09	.07	.62
Phonological Awareness		.10	.09	.12	1.11		.10	.09	.12	1.10
Articulation Speed		- 1.06	.51	-.20*	-2.09		-	-	-	-
Visual Matrix		.14	.10	.16	1.37		-.09	.10	-.10	-.83
Spatial Organization		.18	.10	.20	1.83		.27	.10	.33**	2.72

(table continues)

	Applied Problems – Grade 2					Quantitative Concepts – Grade 2				
Model & Variable	*R²*	*B*	*SE*	*β*	*t* ratio	*R²*	*B*	*SE*	*β*	*t* ratio
5. Phonological Loop	.27					.13				
Age		.01	.10	.01	.08		-.17	.10	-.20	-1.70
Vocabulary		.18	.09	.21*	2.30		.05	.09	.07	.62
Visual Matrix		.14	.10	.16	1.37		-.09	.10	-.10	-.83
Spatial Organization		.18	.10	.20	1.83		.27	.10	.33**	2.72
Phonological Awareness		.10	.09	.12	1.11		.10	.09	.12	1.10
Articulation Speed		- 1.06	.51	-.20*	-2.09		-	-	-	-

Note. **p* < .05. ***p* < .01.

3.2.1. Early Numeracy—First Grade Calculation

In the series of regression analyses to assess the predictors of Calculation in Grade 1, Age and Vocabulary were entered first, but the amount of variance that was accounted for was not statistically detectible (R^2 = .02, F_{inc}(2, 89) = 1.04, p = .359).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness increased the total variance explained by the model to 10%, (R^2 = .10, F(4, 91) = 3.32, p = .024). The introduction of Phonological Awareness explained an additional 8% variance in Grade 1 Calculation, beyond the variance attributed to Age and Vocabulary (ΔR^2 = .08, F_{inc}(1, 88) = 7.73, p = .007). A moderate effect size emerged for Phonological Awareness (β = .31, p = .007).

In the first WM Executive Model (Model 3), entry of Visual Working Memory variables (Visual Matrix and Spatial Organization) increased the total variance explained by the model to 15%, (R^2 = .15, F(4, 91) = 3.72, p = .008). The introduction of Visual Matrix and Spatial Organization explained an additional 12% variance in Grade 1 Calculation, beyond the variance attributable to Age and Vocabulary (ΔR^2 = .12, F_{inc}(2, 87) = 6.29, p = .003). A moderate effect size emerged for Visual Working Memory (Spatial Organization) (β = .41, p = .001).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness explained an additional 8% variance in Grade 1 Calculation, after controlling for variance attributable to Age and Vocabulary (ΔR^2 = .08, F_{inc}(1, 88) = 7.73, p = .007). The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 9% variance in Grade 1 Calculation, (ΔR^2 = .09, F_{inc} (2, 86) = 4.81, p = .010). The total variance explained by the model as a whole was 19%, (R^2 = .19, F(5, 91) = 4.09, p = .002). In the final model, a small effect size emerged for Phonological Awareness (β = .24, p = .030) and a moderate effect size for Visual Working Memory (Spatial Organization) (β = .36, p = .003).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 12%

variance in Grade 1 Calculation after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .12$, $F_{inc}(2, 87) = 6.29$, $p = .003$). The introduction of Phonological Awareness explained an additional 5% variance in Grade 1 Calculation, ($\Delta R^2 = .05$, $F_{inc}(1, 86) = 4.88$, $p = .030$). The total variance explained by the model was 19%, ($R^2 = .19$, $F(5, 91) = 4.09$, $p = .002$). In the final model, a small effect size emerged for Phonological Awareness ($\beta = .24$, $p = .030$) and a moderate effect size for Visual Working Memory (Spatial Organization) ($\beta = .36$, $p = .003$).

3.2.2. Early Numeracy—First Grade Math Fluency

In the series of regression analyses with Math Fluency in Grade 1 as an outcome, Age and Vocabulary were entered first but the amount of variance explained by the two variables together was not statistically detectible, ($R^2 = .01$, $F_{inc}(2, 89) = .45$, $p = .638$).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness after Age and Vocabulary increased the total variance explained by the model to 8%, ($R^2 = .08$, $F(3, 91) = 2.69$, $p = .051$). The introduction of Phonological Awareness explained an additional 7% variance in Grade 1 Math Fluency, after controlling for the variance attributable to Age and Vocabulary ($\Delta R^2 = .07$, $F_{inc}(1, 88) = 7.09$, $p = .009$). A moderate effect size emerged for Phonological Awareness ($\beta = .30$, $p = .009$).

In the first WM Executive Model (Model 3), entry of Visual Working Memory (Visual Matrix and Spatial Organization) increased the total variance explained by the model to12%, ($R^2 = .12$, $F(4, 91) = 2.89$, $p = .027$). The introduction of Visual Matrix and Spatial Organization explained an additional 11% variance in Grade 1 Math Fluency, after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .11$, $F_{inc}(2, 87) = 5.29$, $p = .007$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .38$, $p = .002$).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness explained an additional 7% variance in Grade 1 Math Fluency, after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .07$, $F_{inc}(1, 88) = 7.09$, $p = .009$). The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 8% variance in Grade 1 Math Fluency, ($\Delta R^2 = .08$, $F_{inc}(2, 86) = 3.97$, $p = .022$). The total variance explained by the model as a whole was 16%, ($R^2 = .16$, $F(5, 91) = 3.31$, $p = .009$). In the final model, a small effect size emerged for Phonological Awareness ($\beta = .23$, $p = .037$) and a moderate effect size for Visual Working Memory (Spatial Organization) ($\beta = .33$, $p = .006$).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 11% variance in Grade 1 Math Fluency after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .11$, $F_{inc}(2, 87) = 5.29$, $p = .007$). The introduction of Phonological Awareness explained an additional 4% variance in Grade 1 Math Fluency, ($\Delta R^2 = .04$, $F_{inc}(1, 86) = 4.51$, $p = .037$). The total variance explained by the model was 16%, ($R^2 = .16$, $F(5, 91) = 3.31$, $p = .009$). In the final model, a small effect size emerged for Phonological Awareness ($\beta = .23$, $p = .037$) and a moderate effect size for Visual Working Memory (Spatial Organization) ($\beta = .33$, $p = .006$).

3.2.3. Early Numeracy—Second Grade Calculation

In the series of regression analyses to assess the predictors of Calculation in Grade 2, Age and Vocabulary were entered first, but the amount of variance that was accounted for was not statistically detectible ($R^2 = .02$, $F_{inc}(2, 89) = .78$, $p = .461$).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness increased the total variance explained by the model to 7%, ($R^2 = .07$, $F(3, 91) = 2.33$, $p = .080$). The introduction of Phonological Awareness explained an additional 6% variance in Grade 2 Calculation beyond the variance attributed to Age and Vocabulary ($\Delta R^2 = .06$, $F_{inc}(1, 88) = 5.36$, $p = .023$). A small effect size emerged for Phonological Awareness ($\beta = .26$, $p = .023$).

In the first WM Executive Model (Model 3), entry of Visual Working Memory variables (Visual Matrix and Spatial Organization) increased the total variance explained by the model to 16%, ($R^2 = .16$, $F(4, 91) = 4.09$, $p = .004$). The introduction of Visual Working Memory explained an additional 14% variance in Grade 2 Calculation beyond the variance attributable to Age and Vocabulary ($\Delta R^2 = .14$, $F_{inc}(2, 87) = 7.28$, $p = .001$). A moderate size effect emerged for Visual Working Memory (Spatial Organization) ($\beta = .42$, $p < .001$).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness explained an additional 6% variance in Grade 2 Calculation after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .06$, $F_{inc}(1, 88) = 5.36$, $p = .023$). Addition of Phonological Awareness to the equation did not reliably improve R^2. The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 11% variance in Grade 2 Calculation, ($\Delta R^2 = .11$, $F_{inc}(2, 86) = 5.87$, $p = .004$). The total variance explained by the model as a whole was 19%, ($R^2 = .19$, $F(5, 91) = 3.90$, $p = .003$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .38$, $p = .001$).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 14% variance in Grade 2 Calculation, after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .14$, $F_{inc}(2, 87) = 7.28$, $p = .001$). With Phonological Awareness added to prediction of Calculation ($\Delta R^2 = .03$, $F_{inc}(1, 86) = 2.83$, $p = .096$). Addition of Phonological Awareness to the equation did not reliably improve R^2. The total variance explained by the model was 19%, ($R^2 = .19$, $F(5, 91) = 3.90$, $p = .003$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .38$, $p = .001$).

3.2.4. Early Numeracy—Second Grade Math Fluency

In the series of regression analyses to assess the predictors of Math Fluency in Grade 2, Age and Vocabulary were entered first but the amount of variance explained by the two variables together was not statistically detectible, ($R^2 = .02$, $F_{inc}(2, 89) = .68$, $p = .510$).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness after Age and Vocabulary, increased the total variance explained by the model to 6%, (R^2

= .06, *F(*3, 91) = 2.02, *p* = .117). The introduction of Phonological Awareness explained an additional 5% variance in Grade 2 Math Fluency, after controlling for the variance attributable to Age and Vocabulary (ΔR^2 = .05, F_{inc}(1, 88) = 4.65, *p* = .034). A small effect size emerged for elision (β = .24, *p* = .034).

In the first WM Executive Model (Model 3), after entry of Visual Working Memory (Visual Matrix and Spatial Organization) increased the total variance explained by the model to 17%, (R^2 = .17, *F(*4, 91) = 4.38, *p* = .003). The introduction of Visual Working Memory explained an additional 15% variance in Grade 2 Math Fluency, after controlling for variance attributable to Age and Vocabulary (ΔR^2 = .15, F_{inc}(2, 87) = 7.97, *p* = .001). A moderate effect size emerged for Visual Working Memory (Spatial Organization) (β = .43, *p* < .001).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness explained an additional 5% variance in Grade 2 Math Fluency after controlling for variance attributable to Age and Vocabulary (ΔR^2 = .05, F_{inc}(1, 88) = 4.65, *p* = .034). The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 12% variance in Grade 2 Math Fluency, (ΔR^2 = .12, F_{inc}(2, 86) = 6.58, *p* = .002). The total variance explained by the model was 19%, (R^2 = .19, *F(*5, 91) = 4.00, *p* = .003). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) (β = .39, *p* = .001).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 15% variance in Grade 2 Math Fluency after controlling for variance attributable to Age and Vocabulary (ΔR^2 = .15, F_{inc}(2, 87) = 7.97, *p* = .001). The introduction of Phonological Awareness explained an additional 2% variance in Grade 2 Math Fluency, (ΔR^2 = .02, F_{inc} (1, 86) = 2.24, *p* = .138). Addition of Phonological Awareness to the equation did not reliably improve R^2*.* The total variance explained by the model was 19%, (R^2 = .19, *F(*5, 91) = 4.00, *p* = .003). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) (β = .39, *p* < .001).

3.2.5. Mathematics Word Problem Solving—Second Grade Applied Problems

In the series of regression analyses with Applied Problems in Grade 2 as an outcome, Age and Vocabulary were entered first, ($R^2 = .13$, $F_{inc}(2, 89) = 6.35$, $p = .003$). Vocabulary was statistically significant ($\beta = .28$, $p = .007$).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness and Articulation Speed after Age and Vocabulary increased the total variance explained by the model to 19%, ($R^2 = .19$, $F(4, 91) = 5.11$, $p = .001$). The introduction of Phonological Awareness and Articulation Speed explained an additional 7% variance in Grade 2 Applied Problems after controlling for the variance attributable to Age and Vocabulary ($\Delta R^2 = .07$, $F_{inc}(2, 87) = 3.52$, $p = .034$).

In the first WM Executive Model (Model 3), entry of Visual Working Memory (Visual Matrix and Spatial Organization) increased the total variance explained by the model to 21%, ($R^2 = .21$, $F(4, 91) = 5.90$, $p < .001$). The introduction of Visual Working Memory explained an additional 9% variance in Grade 2 Applied Problems after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .09$, $F_{inc}(2, 87) = 4.90$, $p = .010$). In the final model, small effect sizes emerged for Vocabulary ($\beta = .27$, $p = .007$) and Visual Working Memory (Spatial Organization) ($\beta = .24$, $p = .031$).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness and Articulation Speed explained an additional 7% variance in Grade 2 Applied Problems after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .07$, $F_{inc}(2, 87) = 3.52$, $p = .034$). The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 8% variance in Grade 2 Applied Problems, ($\Delta R^2 = .08$, $F_{inc}(2, 85) = 4.48$, $p = .014$). The total variance explained by the model was 27%, ($R^2 = .27$, $F(6, 91) = 5.17$, $p < .001$). In the final model, small effect sizes emerged for Vocabulary ($\beta = .21$, $p = .043$) and Articulation Speed ($\beta = -.20$, $p = .040$).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 9% variance in Grade 2 Applied Problems, after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .09$, $F_{inc}(2, 87) = 4.90$, $p = .010$). The introduction of Phonological Awareness and Articulation Speed explained an additional 5% variance in Grade 2 Applied Problems, ($\Delta R^2 = .05$, $F_{inc}(2, 85) = 3.14$, $p = .048$). The total variance explained by the model was 27%, ($R^2 = .27$, $F(6, 91) = 5.17$, $p < .001$). In the final model, small effect sizes emerged for Vocabulary ($\beta = .21$, $p < .05$) and Articulation Speed ($\beta = -.20$, $p = .040$).

3.2.6. Knowledge of Mathematical Concepts—Second Grade Quantitative Concepts

In the series of regression analyses with Quantitative Concepts in Grade 2 as an outcome, Age and Vocabulary were entered first but the amount of variance explained by the two variables together was not statistically detectible, ($R^2 = .02$, $F_{inc}(2, 89) = .97$, $p = .381$).

In the first Phonological Loop Model (Model 2), entry of Phonological Awareness after Age and Vocabulary increased the total variance explained by the model to 5%, ($R^2 = .05$, $F(3, 91) = 1.56$, $p = .204$). The introduction of Phonological Awareness explained an additional 3% variance in Grade 2 Quantitative Concepts after controlling for the variance attributable to Age and Vocabulary ($\Delta R^2 = .03$, $F_{inc}(1, 88) = 2.71$, $p = .103$).

In the first WM Executive Model (Model 3), entry of Visual Working Memory (Visual Matrix and Spatial Organization) increased the total variance explained by the model to 12%, ($R^2 = .12$, $F(4, 91) = 2.82$, $p = .030$). The introduction of Visual Working Memory explained an additional 9% variance in Grade 2 Quantitative Concepts after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .09$, $F_{inc}(2, 87) = 4.58$, $p = .013$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .35$, $p = .004$).

In the second WM Executive Model (Model 4), the introduction of Phonological Awareness explained an additional 3% variance in Grade 2 Quantitative Concepts, after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .03$, $F_{inc}(1, 88) = 2.71$, $p = .103$). Addition of Phonological Awareness to the equation did not reliably improve R^2. The introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 8% variance in Grade 2 Quantitative Concepts, ($\Delta R^2 = .08$, $F_{inc}(2, 86) = 3.76$, $p = .027$). The total variance explained by the model was 13%, ($R^2 = .13$, $F(5, 91) = 2.50$, $p = .037$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .33$, $p = .008$).

In the second Phonological Loop Model (Model 5), the introduction of Visual Working Memory (Visual Matrix and Spatial Organization) explained an additional 9% variance in Grade 2 Quantitative Concepts after controlling for variance attributable to Age and Vocabulary ($\Delta R^2 = .09$, $F_{inc}(2, 87) = 4.58$, $p = .013$). The introduction of Phonological Awareness explained an additional 1% variance in Grade 2 Quantitative Concepts, ($\Delta R^2 = .01$, $F_{inc}(1, 86) = 1.21$, $p = .275$). The addition of Phonological Awareness to the equation did not reliably improve R^2. The total variance explained by the model was 13%, ($R^2 = .13$, $F(5, 91) = 2.50$, $p = .037$). In the final model, a moderate effect size emerged for Visual Working Memory (Spatial Organization) ($\beta = .33$, $p = .008$).

3.3. Summary

In summary, the important findings from the hierarchical regression analyses are as follows. First, after controlling for Age and Vocabulary, the predictors of each mathematics outcome variable differed as children progressed from Grade 1 to Grade 2. While both Visual Working Memory (Spatial Organization) and Phonological Awareness contributed unique variance to Calculation and Math Fluency in first grade, only Visual Working Memory explained unique variance in these mathematical outcomes in second grade. Second, Phonological Awareness and Articulation Speed appear to be tapping somewhat different components within the phonological loop, as Phonological Awareness and Articulation Speed each predicted different mathematical outcomes. In Grade 1, Phonological Awareness, but not Articulation Speed contributed to Calculation and Math Fluency. In Grade 2, Phonological Awareness did not predict mathematical outcomes; however, Articulation Speed was the only variable that contributed unique variance to the prediction of Applied Problems. Third, while Visual Matrix did not contribute unique variance to any of the mathematical outcomes, Spatial Organization explained unique variance in both first and second grade Calculation, Math Fluency, and Quantitative

Concepts. Taken together, these findings suggest that the working memory system that underlies children’s early mathematics achievement changes over time as children’s knowledge of mathematics concepts emerges. These findings are discussed in detail and in relation to the research question posed in the next chapter of the thesis.

Chapter 4.

Discussion

The purpose of this study was to explore whether the working memory system available to children in Kindergarten predicts their mathematics achievement in Grades 1 and 2. Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) guided predictions and interpretation of the findings. Specifically, performance on measures associated with the central executive and phonological loop were expected to predict unique aspects of mathematics achievement as children progressed through the primary grades. The theoretical and educational implications of the study findings are also considered along with directions for future research. Limitations of the study are also examined.

Findings from this research indicated that children's performance on measures associated with the central executive and phonological loop in Kindergarten predicted their ability to perform computations with single and double-digit numbers at the end of the first grade, however, the performance on measures associated with the central executive alone predicted more complex computational skills in second grade. Phonological awareness remained an important predictor of language-related mathematics skills in second grade, including knowledge of mathematics concepts and mathematics word-problem solving. Kindergarten children's performance on measures of the central executive also contributed unique variance to the prediction of knowledge of mathematical concepts in second grade; however contrary to expectations, performance on measures affiliated with the central executive was not associated with children's ability to solve mathematics word problems.

In general, these findings affirm that estimates of Kindergarten-aged children's capacity for processing in the phonological loop and the central executive predict emergence of early calculation skills in the first grade; however the relations of the working memory system available to children in Kindergarten and mathematics skills in second grade is more complex. To further explore this complexity, study findings are discussed in relation to other research on the roles of the phonological loop and the central executive in mathematics achievement.

4.1. Role of the Phonological Loop

One issue addressed in this research concerns whether articulation speed and/or phonological awareness in the phonological loop contribute to children's mathematics achievement in the primary grades. As previously discussed, phonological awareness and articulation speed may both be influenced by the stability of phonological representations in long-term memory. However, this was not supported in the current research because the association between performance on the two measures was not statistically detectible. The research findings support an alternate view that phonological awareness and articulation speed are unique constructs. The pattern of associations found between Kindergarten-aged children's ability to process information in the phonological loop and their mathematics achievement in later years differed depending on which of these two measures of phonological processing was involved.

Phonological awareness appears to be important to the prediction of children's computation accuracy and speed in first grade, and their knowledge of mathematics concepts and problem solving ability in second grade. According to Baddeley (1986), phonological representations in long-term memory are retrieved and temporarily stored in the phonological loop as children construct spoken words. Following Piaget (1963), Mead (1934) and others, these spoken words are integrated into the internal action plans that guide children's behaviour, such as when they are counting numbers in serial order and/or computing calculations using numeric (linguistic) symbols (Geary, 1993; Simmons & Singleton, 2007). As children repeat these actions, they utilize these linguistic tools to reflect on their actions, which in turn, leads to the construction of conceptual knowledge about mathematics. It follows then, that phonological awareness in Kindergarten might be a good predictor of children's ability to engage in language-based mathematics activities in first and second grade.

The relations between phonological awareness and children's computational ability appears to shift over time. Findings from the current study showed that while phonological awareness in Kindergarten was associated with children's accuracy and speed of calculations at the end of first grade, the prediction was non-significant when the same outcomes were estimated at the end of second grade. At first glance, this finding is unexpected, because previous research has shown that among children in the upper elementary grades (i.e., Grades 3 to 6), a significant relationship exists between phonological awareness and children's computational skills (Berg, 2008; Fuchs et al., 2006; Hecht et al., 2001; Vukovic & Lesaux, 2013). However, two explanations are available to rationalize these seemingly discrepant results.

First, it is well documented that rapid growth in phoneme awareness occurs over the primary years (Berninger, Abbott, & Nagy, 2010); therefore, it seems reasonable to assume that children's phonological awareness in Kindergarten may have little to do with their ability to retrieve and manipulate phonological information two years later, at the end of Grade 2. Children's ability to perform complex calculations at the end of second grade may be more associated with phonological awareness abilities that are also more complex than those estimated in Kindergarten.

A second explanation of the findings is that differences in the complexity of the computations that children learn in first and second grade may account for the finding that phonological awareness in Kindergarten predicts first, but not second grade computational ability. Findings of a study (de Smedt, Taylor, Archibald, & Ansari, 2010) examining the association between phonological awareness and computational abilities in typically developing fourth and fifth grade children lend some support to this idea. Results showed that phonological awareness was associated with children's ability to compute additions, subtractions, and multiplication with single digit numeric symbols; however, the association was lost when children were asked to compute more complex algorithms with two or more digit numeric symbols. De Smedt et al. (2010) suggest that in order to calculate complex computations, children must engage in the use of more complex procedural strategies that likely involve processing beyond the phonological system. Similarly, in the current research, phonological awareness in Kindergarten was associated with calculations taught as part of a first grade curriculum, but a working memory executive system was more important to more complex calculations in the second grade.

Taken together, the findings from the current and past research suggest that phonological awareness contributes to computational ability in both younger and older children in the elementary grades; however, the strength of this association is greater when phonological awareness is measured closer in time with computational skills and/or when the computational task requires less complex procedural strategies. When the computational task is more complex, it appears that the central executive alone explains variance in performance.

A markedly different pattern of findings emerged when articulation speed in Kindergarten represented processing in the phonological loop. Articulation speed explained variability only in performance on second grade mathematics word problems. The associations between articulation speed and computational fluency in first and second grades and knowledge of mathematical concepts in the second grade were not statistically detectible. One explanation of these findings comes from the work of researchers (e.g., Bowers & Swanson, 1991; Kail & Salthouse, 1994) who argue that articulation speed in Kindergarten may be a better measure of general processing speed than of the rate of processing phonological information. While not conclusive, evidence in support of this view comes from the finding that the correlation between phonological awareness and articulation speed in Kindergarten was not statistically significant and both measures predicted different aspects of mathematics achievement.

An alternative explanation of the findings discussed above is that Kindergarten-aged children are still learning to speak in their language of cultural origin; therefore, their articulation speed may be slower at this young age because the phonological representations of spoken words in long-term memory may be poorly formed or unstable. Gathercole (2006) argued that when phonological representations are not well defined, processing in the phonological loop is inefficient, resulting in slower rates of articulation speed on rapid naming tasks. It follows then, that when phonological representations of spoken (number) words in long-term memory are not well-formed or unstable, retrieval of these words into the phonological loop is also slower and less accurate; which means that the speed of children’s mental computations will also be slower (Fuchs et al., 2006; Hecht et al., 2001; Geary, 1993; Swanson & Kim, 2007; Vanbinst, Ceulemans, Ghesquière, & de Smedt, 2015). Children in the present research were administered measures of articulation speed at the beginning of their Kindergarten year, at a time when their language skills are still developing. While the children were able to complete the articulation speed task, their rate of speaking words was slow and they halted several times in their repetitions. It is possible that children's articulation speed in Kindergarten may not have reached a threshold necessary to reliably predict their rate of computing calculations in first and second grade. Computing calculations draws upon children's ability to quickly and accurately retrieve domain-specific mathematics language from first and second grade curricula.

In contrast, the rate of articulation of spoken words in Kindergarten was sufficient to predict children's ability to solve mathematics word problems in second grade. Solving mathematics word problems draws upon children's general language abilities to interpret the mathematics problem. Children who access vocabulary quickly and effortlessly are at an advantage for solving mathematics word problems more efficiently. This interpretation of the findings is consistent with previous research showing that articulation speed contributed significant variance to the prediction of mathematics word problem solving performance in first to third grade children (Swanson, 2011; Swanson & Beebe-Frankenberger, 2004). Findings in the present research extend these findings and show that as early as Kindergarten entry, articulation speed predicts children's ability to solve mathematical word problems two years later in school.

In summary, children's capacity for processing in the phonological loop as well as the central executive early in their Kindergarten year is predictive of their computational abilities in the first and second grades; however, phonological awareness and articulation speed within the phonological loop predict different outcomes in second grade. Phonological awareness predicts children's ability to accurately and quickly perform calculations, theoretically because computing calculations are guided by the use of language within internal action plans. On the other hand, articulation speed appears to be more important for children to efficiently process information within the overall working memory system, and is therefore important to activities that involve integrating diverse forms of information, such as the ones occurring during mathematical word-problem solving.

4.2. Role of the Central Executive

The findings of this study were generally consistent from those reported by others (de Smedt et al., 2009; Fuchs et al., 010; Meyer et al., 2010; Simmons et al., 2012) showing that performance on complex span tasks affiliated with the central executive (listening span, counting span, digit span backward) in Baddeley's (Baddeley & Hitch, 1974; Baddeley, 1986, 1996, 2000) model of working memory are associated with the accuracy and speed at which children in the primary grades are able to compute calculations. When the central executive is estimated with a spatial organization task, the pattern of associations between the central executive and first and second grades computational ability is consistent with what has been reported in previous research. However, it is significant to note that this pattern of findings was not obtained in the present research when the verbal story retelling or the visual matrix tasks were used to estimate access to executive resources; a finding that requires some explanation.

The spatial organization task is similar to other working memory span tasks where children are required to encode and retrieve a representation of an array of diverse, identifiable objects (e.g., key, small ball, toy horse). Children may have drawn upon visual information processing strategies as well as verbal labeling strategies to support their recall of identifiable objects in their environments. This interpretation aligns well with findings from a study of first graders conducted by Simmons et al. (2012) that showed that a composite working memory factor generated from measures of both verbal and visual working memory was positively correlated with children's ability to calculate additions with single digit numbers. These findings together suggest that a general working memory executive resource (i.e., where visual and verbal information is integrated) is important to the prediction of children's accuracy and speed of performance on measures of first and second grades calculation and math fluency.

In contrast, on the story retelling task, children were asked to recall events in a story that were prioritized by the children in terms of significance. This approach differs from typical working memory span tasks where children are directed to recall specific information in a specific order. The story retelling task may not have required access to executive resources to the same extent as either verbal working memory span tasks or the spatial organization task in the present study. Therefore, the relationship with mathematics achievement is not statistically detectible.

Similarly, on the visual matrix task, children may have relied solely upon their recall of visual patterns to formulate an accurate response. Spatial organization and visual matrix are moderately correlated and both measures are thought to tap visual working memory. However, the spatial organization task may also have drawn upon children's verbal rehearsal strategies.

The association between the working memory central executive and first and second grade calculation and math fluency appears to be robust across a wide array of tasks that measure children's computational ability (Raghubar, Barnes, & Hecht, 2010). Earlier studies that examined this issue included outcome measures of single-digit addition (Noël et al., 2004; Simmons et al., 2012) or double-digit addition and subtraction (de Smedt et al., 2009; Swanson & Kim, 2007). In the present research, the outcome measures of calculation and math fluency included items that tapped both single- and double-digit addition and subtraction. Computing these calculations involves accessing and retrieving what is, at times, partially formed representational knowledge of mathematical concepts and computational procedures in long term memory into a working memory executive, where this and other information is simultaneously processed to formulate a response.

A similar pattern of findings emerges in the present research when Kindergarten aged children's performance on measures that tap capacity for processing at the level of the central executive is used to predict their conceptual knowledge about mathematics in second grade. Kindergarten performance on the spatial organization task predicted complex forms of mathematical knowledge and reasoning (i.e., knowledge of mathematical concepts, symbols and vocabulary) in the second grade.

Pina, Fleuntes, Castillo, and Diamantopoulou (2014) also found that in a sample of children in Grades 4 to 6, processing affiliated with the central executive component of the working memory system was associated with knowledge of mathematical concepts. Moreover, verbal working memory, estimated by performance on a measure of backwards digit span, was related more to performance on mathematical tasks that required converting mathematical information from a symbolic/visual form to a verbal form, while spatial working memory, estimated from performance on the Corsi blocks task, was necessary to solve mathematical problems that required identification of number patterns. Findings in the present research extend those reported by Pina et al. (2014) and show that among younger children of Kindergarten age, performance on measures of the central executive that integrate visual and verbal information processing predicts children's knowledge of mathematical concepts, symbols, formulas, and vocabulary in second grade. Among younger children the working memory system available to them may not be as differentiated as in older children.

Children's exposure to a mathematics curriculum appears to play a more important role than age in explaining the relations between the working memory system available to children in Kindergarten and their later mathematics achievement. Both the phonological loop and the central executive components of the working memory system available to children in Kindergarten appear to support performance on first grade measures that require conceptual and procedural knowledge about mathematics taught within a first grade curriculum; however, these relations are far more specialized by the time children are exposed to a second grade curriculum.

In summary, findings from the present study suggest that the working memory executive system available to young children in Kindergarten plays an important role in predicting mathematics achievement in the first and second grades. Specifically, study findings revealed that performance on tasks tapping processing in the central executive and phonological loop in Kindergarten together predict first grade calculation and math fluency. However, predictions with later mathematics achievement become more specialized as children grow older and progress through the primary curriculum. For instance, phonological awareness in Kindergarten contributes unique variance to children's ability to identify mathematical concepts; however, articulation speed in Kindergarten is important to solve mathematical word-problems in the second grade. Further, only visual working memory tasks at the executive level that also integrate verbal information predict second grade calculation, math fluency, and mathematical conceptual knowledge.

The general conclusion that can be drawn from these findings is that the executive working memory system available to young children at school entry is predictive of later performance of measures of mathematics achievement. However, these relations change when children move from the first to the second grade. Performance on measures associated with the phonological loop appears to be more important to early numeracy in first grade and mathematics word problem solving in second grade. However, performance on central executive tasks predicted numeracy and mathematical conceptual knowledge in the second grade. Even as early as Kindergarten, the working memory executive system is a reliable predictor of later mathematics achievement. These relations hold irrespective of children's age at Kindergarten entry.

4.3. Limitations of the Study

Several limitations of the present study warrant discussion. First, a substantial amount of the variance in all mathematics outcome variables remained unexplained. Taken together, the predictor variables explained between 13% and 27% of the variance in first and second grade mathematics achievement. A greater amount of variance may have been explained had other correlates of mathematics achievement been included. For example, the influence of informal mathematics knowledge was not taken into account, although previous research has clearly established that it plays an important role in children's emerging mathematical competence (Purpura et al., 2013).

Second, the construct validity of the working memory system was not established in this study. To conduct factor analyses, more measures of the central executive and the phonological loop are required. On a related issue, future research might include measures of short-term memory. In the present research processing in the phonological loop was estimated with measures of phonological awareness and articulation speed. Passolunghi and Lanfranchi (2012) and Swanson and Kim (2007) suggest that phonological short-term memory is an important component of the phonological loop.

Third, in the present study, information about the various instructional practices used in elementary classrooms would have added context by which to interpret findings. Firmender, Gavin, and McCoach (2014) reported that instructional practices that engage Kindergarten, first graders, and second grade students in verbal communication and encourage appropriate mathematical language are related to students' engagement. When teachers model and provide constant exposure to mathematics vocabulary, they influence students' mathematics achievement.

4.4. Implications of the Study

The findings from the present study have theoretical and educational implications. Measures of the phonological loop and central executive components of the working memory system may be valuable assets in early screening batteries to identify children at risk for possible mathematical learning disabilities. Future research is also required to determine whether Kindergarten aged children can be taught strategies to compensate for age-related limitations in the central executive component of working memory. Given the significance of the phonological loop for the development of mathematics abilities, it seems important that early interventions to improve mathematical outcomes in later grades be comprehensive and include training in phonological awareness and articulation speed.

Recently, researchers have attempted to determine whether working memory training can influence mathematics skills. Kroesbergen, van 't Noordende, and Kolkman, (2014) investigated the effects of two different versions of working memory training on working memory and early numerical skills, (i.e., quantity discrimination and counting) in Kindergarten children. The first training required children to remember, process, and simultaneously activate information (e.g. in one game children had to list items that are taken on a holiday after recalling all previously mentioned items by other players). The second training required children to remember, process, and simultaneously activate numerical and counting information (e.g., in one game children had to list the number of items that are taken on a holiday after recalling the number of previously mentioned items by other players). After eight 30-minute training sessions over a four-week period, children in the two experimental groups displayed medium-to-large effects in their working memory skills as a result of participating in activities requiring them to memorize, process, and activate information. They also outperformed controls on verbal working memory and on early numeracy skills. While the results of Kroesbergen and colleagues (2014) contribute to the discussion concerning working memory training, more research is needed to investigate if mathematical skills could be improved as a result of working memory training and to compare the effects of such training versus direct mathematics training on mathematical performance.

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