Cognitive Impairments of Children with Severe Arithmetic Difficulties: Cognitive Deficit or Developmental Lag?

Derek H. Berg
Mount Saint Vincent University

Abstract

An age-matched/achievement-matched design was utilized to examine the cognitive functioning of children with severe arithmetic difficulties. A battery of cognitive tasks was administered to three groups of elementary aged children: 20 children with severe arithmetic difficulties (SAD), 20 children matched in age (CAM) to the children with SAD, and 20 younger children matched in arithmetic achievement (AAM) to the children with SAD. Measures were related to processing speed, short-term memory, verbal working memory, and visual-spatial working memory. Results suggest three important findings. First, in contrast to previous studies, children with SAD did not show a processing speed impairment. Second, children with SAD were impaired in short-term memory for numerical and non-numerical information. And third, while children with SAD displayed working memory impairments, these impairments were not uniform within verbal working memory or visual-spatial working memory. Taken together, findings indicate that previous studies that have reported differences between children with SAD and their normally achieving peers might have overestimated or mischaracterized the differential cognitive functioning of these groups. Results are discussed within a framework that views the cognitive functioning impairments of children with SAD as representative of a developmental lag rather than a cognitive deficit.

An inability to develop early proficiency in mathematics has long-term implications. Like those who experience difficulty in reading, those who experience difficulty in mathematics face significant challenges in daily living (Stevenson, 1987) and in employment (Paglin & Rufolo, 1990; Rivera-Batiz, 1992). Changing trends within society and within curriculum further complicate favourable long-term outcomes for those who do not develop proficiency in mathematics. Indeed, mathematics has become a critical filter for employment and full societal participation (National Council of Teachers of Mathematics, 1989). The consequences of poor mathematical development are perhaps most prominent for those whose difficulty in mathematics is so profound that it is typically labelled as a disability. For 30 years research has reported that 6-7% of the elementary school population has a math disability (Badian, 1983; Kosci, 1974; Rivera, 1997), rates that are similar to those reported for children with a reading disability (e.g., Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998). As well, similar to reading, early difficulties experienced by children with math disabilities result in a developmental trend such that for every two years these children spend in school they acquire only one year of mathematical skill (Cawley & Miller, 1989). While substantial progress has been made in identifying the cognitive processes that contribute to reading proficiency and reading disabilities (e.g., phonological processing, Snow, Burns, & Griffin, 1998; Stanovich, 1982), a notable lack of attention has been focussed on identifying the cognitive processes that undergird mathematical proficiency and math disabilities. Identification of the cognitive underpinnings of proficient and of unsuccessful development of mathematics abilities would facilitate the development of instructional strategies to assist positive and to counter negative short-term and long-term outcomes.

One of the most consistent findings across studies examining the mathematics performance of children with math disabilities (MD) is their failure to develop proficiency in arithmetic calculation, such as addition (e.g., $7 + 6$). For instance, children with MD appear to be slower at developing proficiency for arithmetic facts than their normally achieving peers (Geary, 1987, 1990, 1993; Jordan, Hanich, & Kaplan, 2003). Specifically, compared to their normally achieving peers, children with MD tend to be less accurate (e.g., Ostad, 1998) and tend to provide correct answers more slowly (e.g., Jordan & Montani, 1997). In producing solutions to addition problems, children with MD rely upon inefficient manual calculation strategies (e.g., finger counting) well beyond the stage when they are expected to have moved to more efficient strategies such as direct retrieval from long-term memory (e.g., Geary, 1990; Geary & Brown, 1991). In light of the difficulties children with MD experience performing arithmetic calculation, memory functioning and memory-related processing abilities have moved to the forefront as potential explanations for

cognitive functioning differences that characterise children with MD. However, a concomitant focus of research to identify specific cognitive impairments of children with MD has been limited. The purpose of the present study was to investigate whether children with MD, compared to their normally achieving peers, are characterised by impairments in three cognitive domains that have received the bulk of attention in arithmetic calculation: working memory, short-term memory, and processing speed.

Working Memory

Working memory is the ability to maintain information in conscious attention while concurrently processing the same or other information (Baddeley, 1986, 2001; Baddeley & Logie, 1999). A growing body of research has examined the working memory functioning of children with MD and children normally achieving in mathematics (e.g., Bull & Johnston, 1997; Geary, Brown, & Samaranayake, 1991; Hitch & McAuley, 1991; Siegel & Ryan, 1989; Swanson, 1993, 1994). In general, these studies report that children with MD have poorer working memory than their normally achieving peers, with specific differences related to individual working memory components. Several studies have reported that children with MD perform more poorly than do normally achieving children on verbal working memory tasks (Bull & Johnston, 1997; D'Amico & Guarnera, 2005; Hitch & McAuley, 1991; Passolunghi & Siegel, 2001; Swanson & Sachse-Lee, 2001). Moreover, the verbal working memory impairments in children with MD have been found for a range of ages and on a variety of measures. Geary and colleagues reported that children with MD in first grade and second grade have lower digit spans than their mathematically normally achieving same-age peers (e.g., Geary, 1990; Geary et al., 1991). In support of Geary et al.'s findings, Hitch and McAuley (1991) found similar results on a digit span task, but reported an additional verbal working memory impairment in children with MD on a counting span task. Results across studies, however, suggest that there is a lack of consensus of a general verbal working impairment in children with MD. Passolunghi and Siegel (2004) found that the performance of children with MD on a digit span backward task, a counting span task, and a listening span task was poorer than their same-age normally achieving peers, yet the performance of MD children on a backward word span task did not differ between these groups.

Similar to studies examining the verbal working memory functioning of children with MD, studies have also shown visual-spatial working memory impairments in these children (Bull, Johnston, & Roy, 1999; D'Amico &

Guarnera, 2005; McLean & Hitch, 1999). Further, visual-spatial impairments have been found on a range of visual-spatial tasks, such as a matrix span task (D'Amico & Guarnera, 2005) and the Corsi Block task (McLean & Hitch, 1999). So prominent are the visual-spatial impairments of children with MD that current definitions include subtypes that refer specifically to visual-spatial processing impairments (Geary, 1993; Robinson, Menchetti, & Torgesen, 2002; Rourke, 1993). Again, similar to studies investigating verbal working memory, research examining the visual-spatial working memory functioning of children with MD has not consistently reported performance differences between their normally achieving peers. Bull et al. (1999) reported that children with MD did not differ from normally achieving children in mathematics on visual-spatial working memory using the Corsi Block test. However, their participants' mean age was 7 years. It is possible that at this age, visual-spatial working memory, and in particular the spatial-sequential nature of the Corsi Block test, is not fully developed. If so, then a performance difference may not be observable. Indeed, research suggests that visual-spatial abilities are relatively static until the period from 8 years of age to 11 years of age (Cornoldi & Vecchi, 2003).

Other than the general agreement that children with MD show working memory impairments, there is no consensus indicating a specific working memory profile of these children. For instance, although research indicates that children with MD perform more poorly on verbal working memory tasks than their mathematically normally achieving peers, literature is inconsistent on whether children with MD are characterised by an impairment specific to verbal working memory. For instance, McLean and Hitch (1999) reported that children with MD performed poorer than children without MD on visual-spatial working memory tasks but not on verbal working memory tasks. In contrast, Geary, Hoard, Byrd-Craven, and DeSoto (2004) reported that children with MD performed more poorly than their same-aged peers on verbal working memory but not visual-spatial working memory.

Discrepancies in findings across studies might be a result of methodological differences among studies such as selection criteria, definitions of disability, and instrumentation. It is not uncommon for studies to administer one or two tasks that measure working memory (e.g., counting span; Barrouillet & Lépine, 2005) and attribute performance on these measures to general working memory functioning (Mabbott & Bisanz, 2003). Typically, however, the measures selected are representative of a single working memory component. While the use of disparate verbal working memory measures across studies suggests a specific verbal working memory impairment in children with MD that is reflective of a range of verbal memory processes, an interpretation from

within individual studies of a general verbal working memory impairment based upon individual measures must be made with caution. For instance, in a counting span task, a child is asked to count a series of visual arrays of items and is then asked to remember the total count for each array. The span score is the number of array totals the student is able to recall correctly. Given the differences noted between children with and without MD in counting (Geary et al., 1991, Geary, Bow-Thomas, & Yao, 1992), with better counting ability favouring normally achieving children, the source of differences in counting span tasks between these two groups is questionable. Does a significant difference denote a working memory impairment or a counting impairment? Further, Barrouillet and Lépine (2005) used a counting span task to assess verbal working memory. Without including measures of visual-spatial working memory, studies risk masking the potential influence of visual-spatial working memory and risk over-emphasising the importance of verbal working memory functioning.

Similarly, when attending to both verbal working memory and visual-spatial working memory, studies generally administered one or two measures representative of each component. The challenge of this methodology is that singularly or in combination, measures of a specific working memory component might fail to identify specific impairments that are idiosyncratic to a particular measure. Researchers risk misinterpreting individual functioning on a particular measure as indicative of working memory ability when a more fitting interpretation might rest in procedural or academic difficulties. For instance, in the case of counting span, given that children with MD generally perform poorly on counting tasks (Geary et al., 1991, 1992), does a significant difference between children with and without MD denote a counting impairment or a working memory impairment? To address these challenges the field would benefit from an examination of the working memory functioning of children with MD using a wider range of measures and measures specific to each working memory component.

Short-term Memory

While working memory is viewed as the ability to store and processes information concurrently, the latter element is important because it serves to distinguish working memory from other forms of memory such as short-term memory. In brief, short-term memory is often viewed as similar to working memory because of the similar storage function, while these memory systems are seen as different in light of the processes function of working memory

(Baddeley, 1986; Just & Carpenter, 1992; see Unsworth & Engle, 2007 for an alternative view). Short-term memory has been associated with the development of academic skills (Hitch & McAuley, 1991; Swanson, 1993). Specific to mathematics, several studies report that compared to their mathematically normally achieving peers, children with MD perform more poorly on a range of short-term memory tasks (Bull & Johnston, 1997; Siegel & Ryan, 1989). In their study examining relationships between mathematics and cognitive processing in 7-year-old children with and without MD, Bull and Johnston (1997) reported that children with MD performed more poorly than their peers on short-term memory measures for numeric and nonnumeric information. In a similar study with 9-year-olds, McLean and Hitch (1999) did not find a significant difference between children with MD and normally achieving children on short-term memory for numeric and nonnumeric information. Disparate results between these studies are likely to be a product of the influence of reading. Indeed, Bull and Johnston (1997) found that group differences on the short-term memory tasks disappeared after controlling for the significant group difference in reading ability. Further, in the McLean and Hitch (1999) study, children with MD and normally achieving children were comparable in reading ability, which might have influenced the absence of group differences on the short-term memory tasks.

While reading seems to influence performance differences in short-term memory between ages 7 and 9 years, a question arises whether this similarity in performance is stable over time. The capacity of short-term memory increases from pre-school through the elementary school years and on through adolescence (e.g., Swanson, 1996; Verhaeghen & Salthouse, 1997). For example, pre-school children can hold three to four numbers in short-term memory whereas a child in fourth grade can hold five to six numbers in short-term memory (Kail, 1990). It might be that the short-term memory functioning of children with MD does not progress at the same rate as their normally achieving peers. If so, a functional difference might surface later in development.

Processing Speed

With respect to group differences in processing speed, the maximum rate that cognitive functions are performed (Kail, 1992), studies have found significant differences between children with and without severe learning difficulties (Kail, 1994; Martos, 1995). These differences have been noted on tasks that assess auditory-based information (rapid naming of speech and non-speech tones; Waber et al., 2001) and visually-based information (parallel and serial

filtering task; Weiler et al., 2000). While the majority of these studies have focussed on reading difficulties and others have suggested the role of processing speed as a component in the double-deficit theory of reading disabilities (Wolf & Bowers, 1999), the few studies in the area of mathematics have also suggested the importance of processing speed. A marked impairment quickly accessing and using information stored in long-term memory has been argued to be a defining characteristic of the inability of children with MD to develop proficiency in mathematics (Geary, 1990, 1993). Difficulty accessing information from long-term memory has been reported in several studies using a range of measures and methodologies. McLean and Hitch (1999) reported that children with MD were characterised by a marked deficit in accessing long-term memory. Using a missing items task designed to measure a child's ability to hold and to manipulate information retrieved from long-term memory, these researchers found that children with MD performed more poorly than their same-age normally achieving peers.

Articulation speed, the ability to retain verbal-based information in conscious attention, has also been suggested to play a role in the difficulty children with MD have performing arithmetic calculations. Geary (1993) suggested that arithmetic calculation is related to an individual's ability to maintain an association between the component parts of a problem (e.g., partial results) while performing an additional step (e.g., borrowing or regrouping). For instance, slower articulation speed increases the amount of time between counted answers and a combined set of addends to an answer. This increase in time between paired associations increases the potential for decay on one or more of the pieces of information to be remembered, and thus, decreases the likelihood for encoding the paired association into a long-term memory representation.

A third cognitive process that is suggested to be impaired in children with MD is counting speed. The importance of counting speed rests in its relationship to working memory and mathematics. High and low working memory functioning have been associated with parallel performance in counting speed. Case, Kurland, and Goldberg (1982) reported that in children, high working memory capacity was associated with faster counting speed and low working memory capacity was associated with slower counting speed. Although only a few studies have examined counting speed in children with MD, studies do report that these children count slower than their peers without MD (Bull & Johnston, 1997; Geary et al., 1991, 1992; Landerl, Bevan, & Butterworth, 2004). While Passolunghi and Siegel (2001) did not find significant differences between children with and without MD in counting speed, these researchers did report that children with MD were slower at initiating item counting. Given the strong theoretical association between processing speed

and arithmetic calculation and the dearth of empirical research in the area, a more clear understanding of the processing speed functioning of children with MD is necessary.

Cognitive Deficit or Developmental Lag

A central tenet to identifying the cognitive profile of children with MD is to distinguish between those abilities that are idiosyncratic traits of the disorder and those states that reflect intermittent difference during development. Said differently, are significant group differences between children with and without MD representative of a cognitive deficit or a developmental lag? A cognitive deficit suggests that children with MD progress along a qualitatively different developmental path, a sequence of steps different than their normally achieving peers (Stanovich & Siegel, 1994). In contrast, a developmental lag suggests that children with MD and normally achieving children progress along the same developmental path (Stanovich & Siegel, 1994).

Much of the research that has examined the cognitive functioning of children with and without MD compared groups of similar chronological age (e.g., Geary, Hoard, & Hamson, 1999). Further, it is not uncommon for these studies to characterise a cognitive impairment as a deficit (e.g., Bull & Johnston, 1997; Geary et al., 1999; Passolunghi & Siegel, 2001). An age-matched design is inadequate to specify those cognitive processes that relate to a particular area of academic difficulty, as any observed cognitive impairment might be a consequence of low academic achievement, rather than a cause of low academic achievement. Vellutino, Pruzek, Steger, and Meshoulam (1973) suggested the use of a younger achievement-matched group to control for achievement related effects. The rationale follows that if poor achievers perform worse on a cognitive task than their younger normally achieving peers then their poor cognitive performance is less likely to be a result of low academic achievement (a developmental lag), and more likely to be a product of an underlying cognitive deficit.

The Present Study

Across the literature in the field of education and psychology, a range of terms has been used to describe children who experience significant challenges in developing basic mathematics abilities: mathematics difficulties (Gersten, Jordan, & Flojo, 2005; Hanich, Jordan, Kaplan, & Dick, 2001); mathematics

disabilities (Geary, 1993, 2004), dyscalculia (Shalev & Gross-Tsur, 2001), and poor math achievement (Mazzocco & Myers, 2003). These terms are often used interchangeably within the literature. The term *severe arithmetic difficulty* was used to describe the participants in the current study and was used to describe findings from previous studies that used terms such as math disabilities and math difficulties. Adoption of this term was based upon a three-part rationale. First, the term disability suggests an underlying condition marked by a persistent cognitive processing impairment. To date, research has yet to reach consensus on cognitive processes that represent the core deficit or deficits in individuals with math disabilities (Geary, 2004, 2005; Gertsen et al., 2005).

Thus while the current study and research in general in the field of math disabilities assumes an underlying cognitive or neurological impairment is at the root of math disabilities, the term disability may be premature and the term difficulty was used. Second, children were classified as having difficulty in mathematics based upon their scores on a standardised achievement test (Wide Range Achievement Test–Third Revision, WRAT3). Reference to severe was used to indicate the low range of scores on the WRAT3 used to classify students having difficulty in mathematics. Given that students were classified as having a difficulty if they scored at or below the 25th percentile (representing roughly a two year difference in normal mathematics achievement from their same age peers), the term severe represented the lowest quartile on the mathematics achievement continuum. Severe was viewed as more appropriate given that a score below the 50th percentile and above the 25th percentile could reasonably be referred to as indicating a general level of difficulty. Third, as the WRAT3 arithmetic subtest was used to classify students having difficulty, the term arithmetic was used rather than mathematics. Mathematics is a more general term representing many areas of mathematics ability including problem solving, algebra, and geometry, whereas arithmetic is more typically used to refer to computational ability.

In view of the limited number of studies and of the inconsistent findings across studies, there is an absence of consensus about which cognitive functions reflect specific impairments for children with SAD. Further, in light of the methodological characteristics of previous studies, it is unclear whether cognitive impairments of children with SAD reflect cognitive deficits or developmental lags. Two issues challenge the valid interpretations based upon many previous studies. First, when studies address working memory from a componential perspective, many typically use a single task to assess a particular working memory component (e.g., Corsi Block for visual-spatial working memory; Bull et al., 1999). To address this issue, a battery of working memory tasks, with several measures representative of verbal working memory and

of visual-spatial working memory, were administered. A second challenge of previous research is a lack of attention directed at examining the short-term memory functioning and processing speed of children with SAD. In light of the role that short-term memory and processing speed are reported to play in arithmetic performance, it is plausible that these cognitive domains would be implicated in the cognitive impairments that characterise children with SAD. To address the paucity of attention in these areas, two short-term memory tasks and three processing speed tasks were administered.

These issues merge into a third general challenge to previous research. Many studies that have examined cognitive functioning of children with SAD use same-age normally achieving peers as a comparison group (e.g., Bull & Johnston, 1997; Geary et al., 1999; Passolunghi & Siegel, 2001). Such findings are often interpreted as suggesting that children with SAD are characterised by a cognitive deficit in areas measured. As noted above, such interpretations should be viewed cautiously. One prominent alternative explanation is that different achievement-related experiences contribute to observed differences in performance on individual cognitive tasks and specific academic activities (Stanovich, 1986). To address this issue, a chronological age-matched/arithmetic achievement-matched design was employed. The application of an age-matched/achievement-matched design can assist in a more valid characterisation of a cognitive deficit or developmental lag. That is, if children with SAD perform significantly poorer than their same-age peers and younger children, then this performance difference is more likely to be a cognitive deficit than a development lag. In contrast, if children with SAD perform significantly poorer than their same-age peers, but better than younger children, this difference is more likely to be representative of a developmental lag.

Method

Participants

Children for this study were selected from a larger sample of children participating in a study in southeastern Ontario examining the relationship between arithmetic performance and cognitive processing. Sixty children (aged 89 months to 144 months) were purposefully selected from the larger study to create a group of children with severe arithmetic difficulties and two comparison groups: a younger normally achieving group and a same-age normally achieving group. The socioeconomic status of individual students was not assessed; however, each of the schools that participated in the study was located in a predominately middle-class neighbourhood. All children spoke English

as their first language. No child had been identified as having a neurological disorder (e.g., learning disability) or having English language difficulties that would have made it difficult for the child to complete any of the study activities.

Children were classified into one of three groups: 20 children with severe arithmetic difficulty in grades 3 to 6 (SAD, 6 boys, 14 girls), 20 normally achieving children matched in arithmetic achievement in grades 3 to 4 (AAM, 12 boys, 8 girls) with the SAD children, and 20 normally achieving children matched in chronological age in grades 5 to 6 (CAM, 5 boys, 15 girls) with the SAD children. Children were classified as SAD if their scores were equal to or below the 25th percentile on the arithmetic subtest of the Wide Range Achievement Test-Third Edition (WRAT3-A). This percentile score cut-off has been used by other researchers to identify disparate groups of children normally achieving in arithmetic and children experiencing severe difficulty in arithmetic (e.g., McLean & Hitch, 1999; Siegel & Ryan, 1989; Swanson & Sachse-Lee, 2001). The AAM group was created by calculating the mean raw score on the WRAT3-A of the SAD group and then selecting students from third grade and fourth grade whose raw score on the WRAT3-A was comparable to the SAD group. The CAM group was created by calculating the mean chronological age in months of the SAD group and then selecting students of similar chronological age in months (children in fifth grade and sixth grade) whose score on the WRAT3-A was above the 30th percentile. To account for the effects of reading on group differences in cognitive functioning (e.g., Bull & Johnston, 1997), children in each group were further scrutinised for reading, and included in the study only if their reading scores were above the 30th percentile on the reading subtest of the WRAT3.

Instruments

Children completed two test batteries. The first battery was administered to measure children's academic achievement in arithmetic and reading. A second battery included 13 tasks to measure four cognitive abilities: processing speed, short-term memory, verbal working memory, and visual-spatial working memory.

Academic Achievement

The Wide Range Achievement Test-Third Revision (WRAT3; Jastak & Jastak, 1993) was administered to measure children's arithmetic achievement and reading achievement. The arithmetic subtest focuses upon reading numbers, counting, mental arithmetic, and written calculation. The reading subtest focuses upon recognising and naming letters, and pronouncing words. The WRAT3 has been used extensively to assess children's achievement and to identify children with learning difficulties in arithmetic (e.g., Mabbott & Bisanz, 2003; Wilson & Swanson, 2001). Raw scores and standard scores ($M = 100$, $SD = 15$) based on age-appropriate norms were calculated for each child. These scores were used to form the three participant groups. In the present study, Cronbach alpha for the WRAT3-A and the WRAT3-R measured .84 and .86, respectively.

Cognitive Processing

Processing Speed

Three tasks were administered to assess children's processing speed: digit naming, number articulation, and counting dots.

Digit naming. A digit naming speed task was administered to assess children's speed to retrieve phonological numerical representations from long-term memory. This task was a modified version of a similar task used by Compton (2003). In the present study, children were required to read aloud sets of nine randomly ordered Arabic digits (1 through 9) as accurately and quickly as possible. Two trials were administered separated by a 1-min rest. Each trial contained a different arrangement of digits. A stopwatch was used to measure each child's naming times. Time was started when the researcher turned the card to face the child. Naming rate was calculated by dividing the number of digits read per trial (9–3 digits in each of 3 rows) by the mean time for the two trials. Cronbach alpha for the digit naming task measured .87.

Number articulation. A number articulation task was administered to assess children's speed of speech. This task was adapted from a similar task used by Kail (1997). Children were asked to repeat a pair of single syllable digits as quickly as possible five times. Four trials were administered using the digit pairs: 1-4, 5-8, 3-6, and 2-9. Each digit pair was presented orally by the researcher to the child. A practice trial was given using (9-8). A stopwatch was

used to measure the time to articulate each digit pair five times. A child's score for this task was his/her articulation rate. Articulation rate was calculated by dividing the total number of digits articulated per trial (10: 2 numbers repeated 5 times) by the mean time for the four trials. Cronbach alpha for the digit articulation task measured .84.

Counting dots. A counting dots task was administered to assess children's counting speed. This task was a modified version of the task used by Temple and Sherwood (2002). The counting dots task consisted of counting a series of black dots 1.5 centimetres in diameter arranged randomly on an $8\frac{1}{2} \times 11$ laminated white card. Seven trials were administered with each trial corresponding to a specific arrangement of dots with a sequence from 3 to 9 dots. The order of administration was the same for each child: 4 dots, 5 dots, 3 dots, 6 dots, 8 dots, 7 dots, and 9 dots. Children were asked to count the dots on each card as quickly as possible without making any mistakes. A stopwatch was used to measure each child's counting times. A child's score for this task was his/her counting rate. Counting rate was calculated by dividing the total number of dots counted across the seven trials ($n = 42$) by the total time for all seven trials. Cronbach alpha for the counting dots task measured .68.

Short-term Memory

Digit and word span forward. Forward span tasks are measures of short-term memory and have been used widely in studies of children with and without difficulties in arithmetic (Andersson & Lyxell, 2007; Bull & Johnston, 1997; D'Amico & Guarnera, 2005). In the first part of the test, the child was asked to listen to a series of items articulated by the researcher. In the digit span task single-digit numbers were used and in the word span task single-syllable words were used. In the second part, the child was asked to repeat the item sequence in the order presented by the researcher. If the child correctly stated the items in correct sequence another trial was administered. Successive trials increased by one item until the child failed two attempts within the same trial. No feedback was given to the child throughout the task. The maximum possible span was nine items. A child's score for this task was the highest number of items correctly recalled in correct sequence. Cronbach alpha for the digit span and word span tasks were .66 and .68, respectively.

Verbal Working Memory

Four tasks were administered to assess children's verbal working memory. Two tasks were taken from the Swanson-Cognitive Processing Test (Swanson, 1995): auditory digit sequence and semantic categorization. The other two tasks were a digit span backward test and a word span backward test.

Auditory digit sequencing. The auditory digit sequence task assessed a child's ability to recall numerical information contained within a short sentence. The researcher read aloud a sentence containing a street address, asked the child a process question ("Now what was the name of the street?"), and then asked the child to recall part of the address. If the child answered the process question incorrectly the task was stopped. If the child answered correctly the child was asked to state the number embedded within the address. If the child correctly recalled the address number the next sentence was administered. Sets ranged from two to nine sentences. A child's score was the number of sets recalled correctly. Cronbach alpha for the auditory digit sequence task measured .66.

Semantic categorisation. The semantic categorisation task assessed a child's ability to recall related words within prearranged groups. The researcher read aloud a set of words with a 2-second interval between words. Next the researcher asked the child a process question ("Which word, _____ or _____, was presented?") and then asked the child to recall each group name and each word within its respective group. If the child answered the process question incorrectly the task was stopped. If the child answered correctly the child was asked to recall the group and the words within that group. If the child responded correctly the next word set was administered. Item set difficulty ranged from one group with two words to eight groups with three words in each group. A child's score was the number of sets recalled correctly. Cronbach alpha for the semantic categorization task measured .64.

Digit and word span backward. Backward span tasks are measures of short-term memory and have been used widely in studies of children with and without difficulties in arithmetic (D'Amico & Guarnera, 2005; Gathercole & Pickering, 2000; Passolunghi & Siegel, 2001). In the first part of the test, the child was asked to listen to a series of items articulated by the researcher. In the digit span task single-digit numbers were used and in the word span task single-syllable words were used. In the second part, the child was asked to repeat the item sequence in the reverse order presented by the researcher. If the child correctly stated the items in correct sequence another trial was administered. Successive trials increased by one item until the child failed two attempts with-

in the same trial. No feedback was given to the child throughout the task. The maximum possible span was nine items. A child's score for this task was the highest number of items correctly recalled in correct sequence. Cronbach alpha for the digit span and word span tasks were .68 and .72, respectively.

Visual-spatial Working Memory

Four tasks were administered to assess children's visual-spatial working memory. Three of the tasks were taken from the Swanson-Cognitive Processing Test (Swanson, 1995): visual matrix, mapping and directions, and picture sequence. The fourth task administered was a Corsi Block task (Corsi, 1972).

Visual matrix. The visual matrix task assessed a child's ability to recall dots arranged within a matrix. The researcher presented the child with a matrix containing a series of dots, gave the child 5 seconds to study the series of dots within the matrix, withdrew the matrix from the child, and then asked the child a process question ("Are there any dots in the first column?"). If the child answered the process question correctly the child was then asked to reproduce the dot arrangement onto a blank matrix of the same size. If the child correctly reproduced the original matrix the next matrix was administered. The items ranged in difficulty from a matrix of 4 squares with 2 dots to a matrix of 45 squares and 12 dots. A child's score was the number of matrices recalled correctly. Cronbach alpha for the visual matrix task measured .65.

Mapping and directions. The mapping and directions task assessed a child's ability to recall a sequence of directions on a map that contained no visual symbol key. The researcher presented to each child a street map that contained a series of dots (signifying streetlights) connected by lines (signifying a route) and labelled with arrows (signifying directions). The child was given 10 seconds to study the map, the researcher withdrew the map, and then asked a process question ("Were there any stoplights in the first column?"). If the child answered the process question incorrectly the task was stopped. If the child answered correctly, the child was asked to select a strategy depicted on a display card that would help them to remember the dots and lines. Next the child was asked to reproduce the lines, dots, and arrows on a blank map. If the child correctly drew all dots, lines, and arrows from the original map the next map was administered. The items range in difficulty from a map of 2 dots and 2 lines to a map of 20 dots and 20 lines. A child's score was the number of maps drawn correctly. Cronbach alpha for the mapping and direction task measured .71.

Picture sequence. The picture sequence task assessed a child's ability to recall shapes presented in specific arrangements. The researcher presented to the child a series of shapes printed individually on cards and provided the child with 10 seconds to study the arrangement. Next the researcher withdrew the cards and asked the child a process question ("Does this card [distractor card] or this card [selected from the set] belong to the sequence of cards I showed you?"). If the child answered the process question incorrectly the task was stopped. If the child answered correctly the child was given the original set (shuffled by the researcher) and asked to place each card in its original location. If the child correctly arranged all the cards, the next picture sequence was administered. The items ranged in difficulty from 3 cards to 11 cards. A child's score was the number of picture sequences correctly reproduced. Cronbach alpha for the picture sequence task measured .63.

Corsi block task. The Corsi Block task (Corsi, 1972), described by Milner (1971), is one of the most widely used measures of visual-spatial working memory (Cornoldi & Vecchi, 2003) and has been used in studies examining the arithmetic performance and visual-spatial abilities of children with and without learning difficulties in arithmetic (D'Amico & Guarnera, 2005; McLean & Hitch, 1999). The Corsi Block task consists of nine blocks arranged randomly on a wooden board (Milner, 1971). The researcher pointed to a sequence of blocks at a rate of one per second. After the researcher completed tapping the sequence the child was asked to replicate the sequence. If the child correctly recalled the sequence of blocks another trial was administered. Successive trials increased by one block until the child failed two attempts within the same trial. No feedback was given to the child throughout the task. The maximum possible span was nine blocks. The score of this task was the highest number of blocks correctly recalled in sequence. Cronbach alpha for the Corsi Block task measured .70.

Procedure

Measures were administered by the author, individually to children in two sessions in a quiet room in each school. Each session lasted approximately 30 minutes. Each session corresponded with one of the test batteries. The WRAT3 was administered in the first session to each child. The cognitive processing battery was administered in the next session. The order of administration of the tasks within the cognitive processing battery was the same for all children. Processing speed tasks were administered first in the following sequence: digit naming, counting dots, and number articulation. Short-term memory tasks

were administered second in the following order: digit span forward and word span forward. Working memory tasks were administered third. The order of the presentation of the working memory tasks taken from the S-CPT was consistent with the procedures described in the manual of the S-CPT. The three working memory tasks not included in the S-CPT (digit span backward, word span backward, and Corsi Block test) were administered immediately following administration of the S-CPT tasks. The digit span backward task was administered first, the word span backward task was administered second, and the Corsi Block task was administered third.

Results

Participant Classification

Means and standard deviations for the measures used to classify participants are shown in Table 1. A series of analyses of variance was conducted to examine whether the three groups corresponded to the selection criterion of the study design. Significant group effects emerged for chronological age, with Tukey tests indicating that children with SAD and CAM children were matched in age ($p = .477$) and both these groups were older than the AAM children ($ps < .001$).

A significant group effect was found for arithmetic. Raw score comparisons on the WRAT3-A showed significant differences between the CAM children and the children with SAD and AAM children. Post hoc comparisons using Tukey tests indicated no significant differences between children with SAD and AAM children ($p = .294$); whereas both groups scored significantly lower than the CAM children ($ps < .001$). Tukey test comparisons of standard scores on the WRAT3-A showed significant differences between children with SAD and the AAM and CAM children. Tukey tests indicated no differences between AAM children and CAM children ($p = .812$), whereas both groups scored significantly higher than the children with SAD ($ps < .001$). In sum, examination of children's raw and standard scores on the WRAT3-A subtest suggested that the classification procedures based on arithmetic achievement created the three discrete groups necessary to fulfill the purposes of the study.

In light of research that suggested children with comorbid severe difficulty in arithmetic and severe difficulty in reading are characterized by lower arithmetic performance and lower cognitive functioning than their peers with only a severe difficulty in arithmetic (Geary, Hamson, & Hoard, 2000; Jordan et al., 2003) analyses were conducted to examine the reading achievement

Table 1
Group Differences for Age and Achievement Test Scores

Tasks	SAD (N = 20)			AAM (N = 20)			CAM (N = 20)			F	p
	M	SD	Range	M	SD	Range	M	SD	Range		
Age (months)	124.75 _a	13.77	102-144	103.90 _b	9.35	89-120	128.60 _a	7.02	118-142	32.48	<.001
WRAT3-A (raw)	26.25 _a	2.83	22-30	25.05 _a	2.50	21-31	32.55 _b	2.16	28-37	51.45	<.001
WRAT3-A (standard)	85.35 _a	4.02	76-90	100.65 _b	8.64	91-117	101.95 _b	6.53	92-115	38.31	<.001
WRAT3-R (raw)	36.80 _a	3.24	31-44	34.10 _b	3.85	24-38	38.90 _a	2.94	34-43	10.24	<.001
WRAT3-R (standard)	105.80	8.62	93-122	111.25	12.96	85-133	108.65	7.22	95-125	1.51	.229

Note. SAD = severe arithmetic difficulties; AAM = arithmetic achievement-matched; CAM = chronologically age-matched. WRAT3-A = Wide Range Achievement Test-Third Edition, arithmetic subtest; WRAT3-R = Wide Range Achievement Test-Third Edition, reading subtest. Means in the same row that do not share a subscript differ at $p < .05$ in the Tukey honestly significant difference comparison.

of the three groups of children. Analyses of variance indicated significant main effects for raw scores but not standard scores on the WRAT3-R. Significant group differences using Tukey tests were found between the AAM children and the children with SAD and CAM children ($p = .036$ and $p < .001$, respectively). No significant differences were found between children with SAD and CAM children ($p = .128$). Standard score comparisons with Tukey tests on the WRAT3-R showed no significant differences among the three groups ($ps > .200$). Taken together, children's raw and standard scores on the WRAT3-R suggested that any cognitive functioning differences among the groups are not likely to be influenced by variation in reading ability (Geary et al., 2000; Jordan et al., 2003).

Group Differences in Cognitive Processing

Processing speed. A series of ANOVAs was conducted for processing speed measures as a function of group (SAD, CAM, and AAM). Results, reported in Table 2, indicated significant group differences on each processing speed task. Post hoc analyses using Tukey tests showed that SAD children and CAM children did not differ in performance on any of the tasks. However, significant age-related differences were found. Tukey tests showed that for naming digits speed, the AAM children performed significantly slower than both children with SAD and CAM children ($p = .006$, $d = 1.12$; $p < .001$, $d = 1.46$, respectively). For number articulation speed, AAM children were statistically slower than CAM children ($p = .005$, $d = 1.00$). On the counting dots task, significant differences emerged between AAM children and both children with SAD and CAM children, with younger children slower than both older groups ($p = .042$, $d = .74$; $p = .001$, $d = 1.12$, respectively). Effect sizes for all significant differences were within the medium to large range (Cohen, 1988).

Short-term memory. A series of ANOVAs was conducted for short-term memory tasks as a function of group (SAD, CAM, and AAM). Results, reported in Table 2, indicated significant group differences on each task. Post hoc analyses on digit span forward using Tukey tests showed that both children with SAD and AAM children scored significantly lower than CAM children ($p = .006$, $d = 1.13$; $p < .009$, $d = .94$, respectively). Children with SAD and AAM children did not differ in performance ($p = .980$). On the word span forward task, children with SAD scored significantly lower than CAM children ($p = .026$, $d = .82$,) but performed similar to AAM children ($p = .897$). As well, there was no significant difference between CAM children and AAM children ($p = .076$). Effect sizes for all significant differences were large (Cohen, 1988).

Table 2
Group Differences for Processing Speed and Short-term Memory Tasks

Tasks	SAD (N = 20)		AAM (N = 20)		CAM (N = 20)		F	p
	M	SD	M	SD	M	SD		
Processing Speed								
Digit Naming	2.77 _a	.44	2.29 _b	.41	2.99 _a	.54	11.48	<.001
Number Articulation	3.75 _{a,b}	.47	3.51 _a	.52	4.02 _b	.49	5.37	.007
Counting Dots	3.20 _a	.56	2.72 _b	.73	3.47 _a	.60	7.03	.002
Short-term Memory								
Forward Digit Span	5.23 _a	.98	5.18 _a	.77	6.03 _b	.72	6.63	.003
Forward Word Span	4.75 _a	.97	4.85 _{a,b}	.59	5.35 _b	.49	4.08	.022

Note. SAD = severe arithmetic difficulties; AAM = arithmetic achievement-matched; CAM = chronologically age-matched. Means in the same row that do not share at least one subscript differ at $p < .05$ in the Tukey honestly significant difference comparison.

Working Memory

Verbal working memory. A series of ANOVAs on verbal working memory measures as a function of group (SAD, CAM, and AAM) indicated significant group effects on three tasks. Comparisons using Tukey tests (see Table 3) indicated that children with SAD scored significantly lower than CAM children on digit span backward ($p = .027$, $d = .78$), word span backward ($p = .002$, $d = 1.00$), and the semantic categorisation ($p = .014$, $d = .96$). Children with SAD did not differ significantly from AAM children on any verbal working memory task. AAM children, however, scored significantly lower than CAM children on digit span backward ($p = .009$, $d = .119$), word span backward ($p = .038$, $d = .86$), and semantic categorisation ($p = .006$, $d = 1.00$). Effect sizes for all significant differences were within the medium to large range (Cohen, 1988).

Visual-spatial working memory. A series of ANOVAs on visual-spatial working memory measures as a function of group (SAD, CAM, and AAM) indicated significant group effects on three tasks. Tukey tests (see Table 3) indicated that children with SAD scored significantly lower than CAM children on Corsi Block ($p = .010$, $d = 1.19$), visual matrix ($p = .001$, $d = 1.10$), and mapping and directions ($p = .041$, $d = .75$). Children with SAD did not differ significantly from AAM children on any visual-spatial working memory task. On only one task did AAM children score significantly lower than CAM children; visual matrix ($p = .021$, $d = .98$). Effect sizes for all significant differences were within the medium to large range (Cohen, 1988).

Discussion

The present study was designed to account for several limitations in previous research through the use of an age-matched/achievement-matched design, an older childhood sample than many studies, a wider range of domain-specific working memory measures, and the inclusion of short-term memory and processing speed measures. Results suggest three important findings. First, in contrast to previous studies, children with SAD did not show a processing speed impairment. Second, children with SAD were impaired in short-term memory for numerical and for nonnumeric information. And third, while children with SAD displayed working memory impairments, these impairments were not uniform within verbal working memory or visual-spatial working memory.

Table 3
Group Differences for Verbal and Visual-Spatial Working Memory Measures

Tasks	SAD (N = 20)		AAM (N = 20)		CAM (N = 20)		F	p
	M	SD	M	SD	M	SD		
Verbal Working Memory								
Backward Digit Span	3.90 _a	1.26	3.78 _a	.72	4.73 _b	.88	5.55	.006
Backward Word Span	3.40 _a	.94	3.70 _a	.57	4.40 _b	1.05	6.85	<.002
Auditory Digit	2.00	.80	2.20	.83	2.50	.83	1.89	.160
Semantic Categorization	1.65 _a	.93	1.55 _a	1.05	2.55 _b	.95	6.35	.003
Visual-Spatial Working Memory								
Corsi Block	5.10 _a	.79	5.35 _{a,b}	.67	5.85 _b	.88	4.49	.012
Visual Matrix	3.40 _a	1.23	3.75 _a	.79	4.65 _b	1.04	7.76	.001
Mapping and Directions	1.90 _a	1.07	1.95 _{a,b}	.95	2.75 _b	1.21	3.90	.026
Picture Sequence	1.40	.68	1.45	.69	1.85	.81	2.29	.111

Note. SAD = severe arithmetic difficulties; AAM = arithmetic achievement-matched; CAM = chronologically age-matched. Means in the same row that do not share at least one subscript differ at $p < .05$ in the Tukey honestly significant difference comparison.

With respect to processing speed, results indicated that children with SAD did not show a processing speed impairment representative of accessing information from long-term memory (i.e., digit naming), processing number sequences (i.e., counting speed), and retaining information actively within conscious attention (i.e., digit articulation). These results are inconsistent with previous research. For instance, a digit naming impairment (Landerl et al., 2004; Swanson & Sackshe-Lee, 2001) and a counting impairment (Geary, 1990; Geary et al., 1991; Geary et al., 1992) have been reported previously for children with SAD. Explanation for the present study's results might reside in the age difference of participants in the current study and in previous studies. Children in the Landerl et al. (2004) study, which used a similar achievement cut-off score criterion to the present study (25th percentile), were approximately 2 years younger than the children in the present study. It is possible that during late childhood the speed of access to long-term memory for children with SAD progresses to a level that corresponds to their same-age peers. Indeed, literature on cognitive processing highlights a progression towards faster processing speeds throughout childhood (Kail, 1994; Salthouse & Kail, 1983). Reference to the absence of a counting performance difference might also be a product of age differences in participants in previous studies and the present study. During early elementary school years, children with SAD show poorer counting skills compared to their same-age normally achieving peers. From 9 years to 12 years, children with SAD increasingly rely on counting as an arithmetic problem solving strategy (Geary, 1993; Geary et al., 1991). In turn, this over-reliance may lead to increased counting proficiency (speed and accuracy) for children with SAD, which in turn would enable these children to close the gap between them and their normally achieving peers.

That children with SAD in the present study showed short-term memory impairments was in contrast to previous research (Bull & Johnston, 1997; McLean & Hitch, 1999), particularly in light of the control implemented for reading ability. The older age of participants in the current study provides support for the hypothesis that specific cognitive impairments might arise at later stages in development. As well, these impairments do not seem to be task specific. Siegel and Ryan (1989) reported that children with SAD in their study were impaired processing numeric-based information (digit span), while these same children performed similarly on nonnumeric-based information (word span) to their same-age peers. The nature of the impairment remains unclear. Some have suggested that a short-term memory impairment in children with SAD is a product of poor access to information in long-term memory (Geary, 1990, 1993; Hitch & McAuley, 1991). However, in the present study, children with SAD did not show an impairment in accessing long-term memory (i.e., digit naming speed). An alternative interpretation might be that children with

SAD are characterized by a storage impairment, particularly in light of the dual impairment in numeric and nonnumeric information represented in both short-term memory and working memory tasks.

While children with SAD appeared to be impaired in verbal working memory and visual-spatial working memory, these impairments were neither equally strong nor uniform across tasks within each working memory subsystem. Of the four verbal working memory measures administered, children with SAD showed impairments on only three measures. Reflective of effect sizes, these children showed strong impairment in digit span backward ($d = .78$), word span backward ($d = 1.00$), and the semantic categorization ($d = .96, p = .014$). Given that these measures include both numeric and nonnumeric information, it seems that the verbal working memory impairment of children with SAD is not, as previously reported (Siegel & Ryan, 1989) specific to numeric information. Similarly, impairments in visual-spatial working memory for children with SAD appeared in three of the four measures administered. Their performance on Corsi Blocks ($d = 1.19$), visual matrix ($d = 1.10$), and mapping and directions ($d = .75$) showed strong impairments. Again, these findings support previous empirical and theoretical work highlighting the importance of visual-spatial abilities as characteristic of the SAD children (Geary, 1993; Robinson et al., 2002; Rourke, 1993).

Taken together, these results suggested two important findings. First, no single working memory component appears to be more representative of working memory impairment than another. It is not uncommon for studies to have administered a single working memory measure to capture general working memory functioning (e.g., digit span backward, Mabbott & Bisanz, 2003). The data presented here illustrate that when examining the working memory functioning of children with severe arithmetic difficulties, it is important to include measures of both verbal working memory and visual-spatial working memory. Second, results demonstrated that children with SAD can show working memory functioning — on some verbal and visual-spatial tasks — that is comparable to their normally achieving peers. And not every measure of a particular working memory component will capture or reflect impairment in children with SAD. This finding supported one of the principal rationales of the current study that called for a more comprehensive examination of the breadth of potential impairments within individual working memory components.

A review of the cognitive functioning comparisons between children with SAD and CAM children and between children with SAD and AAM children, suggest that the cognitive functioning impairments of children with SAD reflected a developmental lag and not a cognitive deficit. Further, as evidenced

by their significantly lower scores on several cognitive tasks compared to CAM children but no significant differences compared to AAM children, the cognitive impairments of children with SAD children reflect a functioning level similar to children approximately two years younger. These findings suggest that the developmental lag might be more pronounced than previously reported. This characterisation is supported by three additional sources of support. First, studies that have reported working memory impairments of children with SAD suggest that their functioning is approximately one year below the level of their same-age peers (e.g., Geary et al., 2004). Second, the current study's sample of children with SAD was larger than many studies in the field ($n = 15$, Geary & Brown, 1991; $n = 12$, Jordan & Montani, 1997; $n = 12$, McLean & Hitch, 1999). And third, all significant differences between children with SAD and their same-age peers reflected medium to large effect sizes.

Limitations and Implications

Generalizability and interpretation of the current study's results are challenged by participant classification procedures used. Assessment of participants' academic achievement and cognitive ability represented a snapshot of their performance during a brief window of time. Use of the term *severe arithmetic difficulty* might have overestimated the nature of a child's academic difficulty. Research by Jordan and colleagues challenged the utility of a classification based upon a single administration because achievement scores tend to be unstable over as little as two years (e.g., Jordan, Kaplan, & Hanich, 2002). Jordan et al. found that for groups of Grade 2 children classified as having severe difficulties in reading, in mathematics, or in reading and mathematics, a subgroup within each of these groups scored within normal range the following year. Further, a subgroup from the normally achieving group scored below normal range and subsequently was classified into one of the three disability groups. Thus, it appears that for a segment of children, poor achievement might not be best characterised as a severe difficulty (a deficit or persistent failure in one or more academic subjects); rather, their difficulty might be more appropriately termed a moderate academic difficulty.

An important direction for future research would be to isolate those children who show low academic achievement over the course of several assessments across two or more years and to compare their cognitive functioning to academically normally achieving children and to children who show academic inconsistencies within a window of one to two years. Such analyses would further our understanding of whether or not children with severe arithmetic

difficulties and children with moderate arithmetic difficulties share the same cognitive impairment profile. As well, these analyses would assist to identify whether the cognitive impairments of children with SAD are best characterised as a cognitive deficit or a developmental lag.

While the present study did not directly investigate the relationship between cognitive functioning and academic performance of children with and without SAD, the results suggest some tentative implications for educators who work with these groups of students. In light of the working memory impairments of children with SAD and the relationships that are reported between working memory and areas of academic performance (e.g., arithmetic, Berg, in press), there is growing evidence that educators need to attend to the complexity and quantity of information that is embedded in academic activities. For instance, in a study examining the role of working memory in classroom activities, Gathercole, Lamont, and Alloway (2006) found that poor performance by children with working memory impairments was associated with forgetting instructions, difficulty sustaining attention when completing complex activities, an inability to manage the concurrent processing and storing requirements of tasks, and a breakdown accessing long-term memory.

References

- Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal of Experimental Child Psychology*, 96, 197-228.
- Baddeley, A. D. (1986). *Working memory*. New York: Oxford University Press.
- Baddeley, A. D. (2001). Is working memory still working? *American Psychologist*, 56, 851-864
- Baddeley, A. D., & Logie, R. H. (1999). The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 26-61). Cambridge, UK: Cambridge University Press.
- Badian, N. A. (1983). Arithmetic and nonverbal learning. In H. R. Myklebust (Ed.), *Progress in learning disabilities* (Vol. 5, pp. 235-264). New York: Grunt & Stratton.

- Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology*, 9, 183-204.
- Berg, D. H. (in press). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology*.
- Bull, R., & Johnston, R. S. (1997). Children's arithmetical difficulties: Contributions from processing speed, item identification, and short-term memory. *Journal of Experimental Child Psychology*, 65, 1-24.
- Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketchpad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology*, 15, 421-442.
- Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386-404.
- Cawley, J. F., & Miller, J. H. (1989). Cross-sectional comparisons of the mathematical performance of children with learning disabilities: Are we on the right track toward comprehensive programming? *Journal of Learning Disabilities*, 23, 250-254, 259.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). New York: Academic Press.
- Compton, D. L. (2003). Modeling the relationship between growth in rapid naming speed and growth in decoding skill in first-grade children. *Journal of Educational Psychology*, 95, 225-239.
- Cornoldi, C., & Vecchi, T. (2003). *Visuo-spatial working memory and individual differences*. New York, NY: Psychology Press.
- Corsi, P. M. (1972). Human memory and the medial temporal region of the brain. *Dissertation Abstracts International*, 34(02), 891B (University microfilms No. AA105-77717).
- D'Amico, A., & Guarnera, M. (2005). Exploring working memory in children with low arithmetical achievement. *Learning and Individual Differences*, 15, 189-202.
- Foorman, B. R., Francis, D. J., Fletcher, J. M., Schatschneider, C., & Mehta, P. (1998). The role of instruction in learning to read: Preventing reading failure in at-risk-children. *Journal of Educational Psychology*, 90, 37-55.

- Gathercole, S. E., Lamont, E., & Alloway, T. P. (2006). Working memory in the classroom. In S. Pickering & G. Phye (Eds.), *Working memory and education* (pp. 219-40). San Diego, CA: Academic Press.
- Gathercole, S. E., & Pickering, S. J. (2000). Assessment of working memory in six- and seven-year-old children. *Journal of Educational Psychology*, 92, 377-390.
- Geary, D. C. (1987). Cognitive addition: On the convergence of statistical and conceptual models. *Bulletin of the Psychonomic Society*, 25, 427-430.
- Geary, D. C. (1990). A componential analysis of an early learning deficit in mathematics. *Journal of Experimental Child Psychology*, 49, 363-383.
- Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin*, 114, 345-362.
- Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities*, 37, 4-15.
- Geary, D. C. (2005). Role of theory in study of learning difficulties in mathematics. *Journal of Learning Disabilities*, 38, 305-307.
- Geary, D. C., Bow-Thomas, C. C., & Yao, Y. (1992). Counting knowledge and skill in cognitive addition: A comparison of normal and mathematically disabled children. *Journal of Experimental Child Psychology*, 54, 372-391.
- Geary, D. C., & Brown, S. C. (1991). Cognitive addition: Strategy choice and speed-of-processing differences in gifted, normal, and mathematically disabled children. *Developmental Psychology*, 27, 398-406.
- Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental Psychology*, 27, 787-797.
- Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology*, 77, 236-263.
- Geary, D. C., Hoard, M. K., Byrd-Craven, J., & DeSoto, M. C. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology*, 88, 121-151.

- Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology*, 74, 213-239.
- Gersten, R., Jordan, N. C., & Flojo, J. R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities*, 38, 293-304.
- Hanich, L. B., Jordan, N. C., Kaplan, D., & Dick, J. (2001). Performance across different areas of mathematical cognition in children with learning disabilities. *Journal of Educational Psychology*, 93, 615-626.
- Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. *British Journal of Psychology*, 82, 375-386.
- Jastak, J. F., & Jastak, S. (1993). *Manual for the Wide Range Achievement Test: Third Revision*. Wilmington, DE: Jastak Associates.
- Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology*, 85, 103-119.
- Jordan, N. C., Kaplan, D., & Hanich, L. B. (2002). Achievement growth in children with learning difficulties in mathematics: Findings of a two-year longitudinal study. *Journal of Educational Psychology*, 94, 586-597.
- Jordan, N. C., & Montani, T. O. (1997). Cognitive arithmetic and problem solving: A comparison of children with specific and general mathematics difficulties. *Journal of Learning Disabilities*, 30, 624-634.
- Just, A. M., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122-149.
- Kail, R. (1990). *The development of memory in children* (3rd ed.). New York: W. H. Freeman and Company.
- Kail, R. (1992). Processing speed, speech rate, and memory. *Developmental Psychology*, 28, 899-904.
- Kail, R. (1994). A method for studying the generalized slowing hypothesis in children with specific language impairment. *Journal of Speech and Hearing Research*, 37, 418-421.
- Kail, R. (1997). Processing time, imagery, and spatial memory. *Journal of Experimental Child Psychology*, 64, 67-78.

- Kosc, L. (1974). Developmental dyscalculia. *Journal of Learning Disabilities*, 7, 164-177.
- Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9 year old students. *Cognition*, 93, 99-125.
- Mabbott, D. J., & Bisanz, J. (2003). Developmental change and individual differences in children's multiplication. *Child Development*, 74, 1-17.
- Martos, F. (1995). Speed of visual information processing in developmental dyslexia. In C. K. Leong & R. M. Hoshi (Eds.), *Developmental and acquired dyslexia* (pp. 51-59). Amsterdam: Kluwer.
- Mazzocco, M. M. M., & Myers, G. F. (2003). Complexities in identifying and defining mathematics learning disability in the primary school age years. *Annals of Dyslexia*, 53, 218-253.
- McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, 74, 240-260.
- Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin*, 27, 272-277.
- National Council of Teachers of Mathematics. Commission on Standards for School Mathematics. (1989). *Curriculum and evaluation standards for school mathematics*. Reston, VA: Author.
- Ostad, S. A. (1998). Developmental differences in solving simple arithmetic word problems and simple number-fact problems: A comparison of mathematically normal and mathematically disabled children. *Mathematical Cognition*, 4, 1-19.
- Paglin, M., & Rufolo, A. M. (1990). Heterogeneous human capital, occupational choice, and male-female earnings differences. *Journal of Labor Economics*, 8, 123-144.
- Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, 80, 44-57.
- Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology*, 88, 348-367.

- Rivera, D. P. (1997). Mathematics education and students with learning disabilities: Introduction to the special series. *Journal of Learning Disabilities*, 30, 2-19.
- Rivera-Batiz, F. L. (1992). Quantitative literacy and the likelihood of employment among young adults in the United States. *The Journal of Human Resources*, 27, 313-328.
- Robinson, C. S., Menchetti, B. M., & Torgesen, J. K. (2002). Toward a two-factor theory of one type of mathematics disabilities. *Learning Disabilities Research*, 17, 81-89.
- Rourke, B. P. (1993). Arithmetic disabilities, specific and otherwise: A neuropsychological perspective. *Journal of Learning Disabilities*, 26, 214-226.
- Salthouse, T. A., & Kail, R. (1983). Memory development throughout the life span: The role of processing rate. In P. B. Baltes & O. G. Brim (Eds.), *Life-span development and behavior* (Vol. 5, pp. 89-116). San Diego, CA: Academic Press.
- Shalev, R. S., & Gross-Tsur, V. (2001). Developmental dyscalculia. *Pediatric Neurology*, 24, 337-342.
- Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development*, 60, 973-980.
- Snow, C., Burns, S., & Griffin, P. (1998). *Preventing reading difficulties in young children*. Washington, DC: National Academy Press.
- Stanovich, K. E. (1982). Individual differences in the cognitive processes of reading: 1. Word decoding. *Journal of Learning Disabilities*, 15, 485-493.
- Stanovich, K. E. (1986). Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. *Reading Research Quarterly*, 21, 360-407.
- Stanovich, K. E., & Siegel, L. S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology*, 86, 24-53.
- Stevenson, H. (1987). The Asian advantage: The case of mathematics. *American Educator*, 47, 26-31.

- Swanson, H. L. (1993). Working memory in learning disability subgroups. *Journal of Experimental Child Psychology*, 56, 87-114.
- Swanson, H. L. (1994). Short-term memory and working memory: Do both contribute to our understanding of academic achievement in children and adults with learning disabilities? *Journal of Learning Disabilities*, 27, 34-50.
- Swanson, H. L. (1995). *Swanson-Cognitive Processing Test*. Austin, TX: PRO-ED.
- Swanson, H. L. (1996). Individual and age-related differences in children's working memory. *Memory and Cognition*, 24, 70-82.
- Swanson, H. L., & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: Both executive and phonological processes are important. *Journal of Experimental Child Psychology*, 79, 294-321.
- Temple, C. M., & Sherwood, S. (2002). Representation and retrieval of arithmetical facts: Developmental difficulties. *Quarterly Journal of Experimental Psychology*, 55, 733-752.
- Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin*, 133, 1038-1066.
- Vellutino, F. R., Pruzek, R., Steger, J. A., & Meshoulam, U. (1973). Immediate visual recall in poor readers as a function of orthographic-linguistic familiarity. *Cortex*, 9, 368-384.
- Verhaeghen, P., & Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and non-linear age effects and structural models. *Psychological Bulletin*, 122, 231-249.
- Waber, D. P., Wolff, P. H., Weiler, M. D., Bellinger, D., Marcus, D. H., Forbes, P., et al. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorder. *Child Development*, 72, 37-49.
- Weiler, M. D., Harris, N. S., Marcus, D. J., Bellinger, D., Kosslyn, S. M., & Waber, D. P. (2000). Speed of information processing in children referred for learning problems: Performance on a visual filtering test. *Journal of Learning Disabilities*, 33, 538-550.

- Wilson, K. M., & Swanson, H. L. (2001). Are mathematics disabilities due to a domain-general or a domain-specific working memory deficit. *Journal of Learning Disabilities, 34*, 237-248.
- Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*, 415-438.

Author's Note

Correspondence concerning this article should be addressed to:
Derek H. Berg, Assistant Professor, Faculty of Education, 166 Bedford Highway, Mount Saint Vincent University, Halifax, NS, B3M 2J6.