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Longitudinal Mediators of Achievement in Mathematics and Reading in Typical and Atypical Development

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Abstract

Longitudinal studies of neurodevelopmental disorders that are diagnosed at or before birth and which are associated with specific learning difficulties at school-age provide one method for investigating developmental precursors of later-emerging academic disabilities. Spina bifida myelomeningocele (SBM) is a neurodevelopmental disorder associated with particular problems in mathematics, in contrast to well-developed word reading. Children with SBM ($n = 30$) and typically developing children ($n = 35$) were used to determine whether cognitive abilities measured at 36 and 60 months of age mediated the effect of group on mathematical and reading achievement outcomes at 8.5 and 9.5 years of age. A series of multiple mediator models showed that: visual-spatial working memory at 36 months and phonological awareness at 60 months partially mediated the effect of group on math calculations; phonological awareness partially mediated the effect of group on small addition and subtraction problems on a test of math fluency; and visual-spatial working memory mediated the effect of group on a test of math problem solving. Groups did not differ on word reading, and phonological awareness was the only mediator for reading fluency and reading comprehension. The findings are discussed with reference to theories of mathematical development and disability and with respect to both common and differing cognitive correlates of math and reading.

Neurodevelopmental disorders are often associated with specific patterns of strengths and difficulties in academic achievement. These dissociations in skill development can be useful for understanding the development of academic abilities and disabilities more generally (Mazzocco, Murphy, & McCloskey, 2007). In particular, disorders that are diagnosed before or at birth and for which modal patterns of academic achievement at school age are known provide the opportunity to use powerful longitudinal designs to examine early developmental precursors of later learning abilities and disabilities. The current study employed a longitudinal multiple mediation design in which children with spina bifida

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myelomeningocele (SBM) and typically developing children were followed from 36 months to 9 years of age to investigate the overlapping and separate contributions of early cognitive abilities to the later development of mathematics and reading.

SBM is a neurodevelopmental disorder diagnosed before or at birth that affects the development of the spine and brain and is associated with a modal cognitive and academic phenotype at school-age in which word reading is well-developed in contrast to deficits in the development of mathematical skills (Ayr, Yeates, & Enrile, 2005; Dennis & Barnes, 2010; Fletcher et al., 2005). About 50% of children with SBM who are not intellectually disabled have math disabilities, or MD (Fletcher et al., 2005). Even when MD is not diagnosed, reading is typically stronger than math (Barnes et al., 2002; 2006). This pattern is found less often in individuals without neurological impairment where there is greater overlap between reading and math skills (Barbarese, Katusic, Colligan, Weaver, & Jacobsen, 2005; Shalev, Auerbach, Manor, & Gross-Tsur, 2000).

Some of the cognitive predictors of reading and mathematics and growth in these academic domains are similar. Phonological awareness has been related to both reading and math (Hecht, Torgesen, Wagner, & Rashotte, 2001; Krajewski & Schneider, 2009), possibly reflecting the importance of high quality phonological representations for some aspects of arithmetic such as fact retrieval (DeSmedt, Taylor, Archibald, & Ansari, 2010). Weak phonological processing early in life could have implications for early and later mathematical development. Although children with SBM have average or better word decoding skills by school-age, there is some evidence that phonological awareness may show delayed development in the preschool years (Barnes et al., 2011).

Verbal working memory has also been related to performance in both academic domains (Christopher et al., 2012; Swanson & Jerman, 2006; Swanson, Zheng, & Jerman, 2009; Raghubar, Barnes, & Hecht, 2010). In reading, verbal working memory is important for assembling speech-based and text-based information, and in math, it supports encoding, retention, and manipulation of verbal codes used for counting, exact arithmetic, and mathematical algorithms (Dehaene, Piazza, Pinel, & Cohen, 2005). One study found that several aspects of mathematical performance of young children with MD are mediated by working memory, particularly by verbal working memory (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007). Verbal working memory is related to math calculations in adults with SBM (Dennis & Barnes, 2002).

There is also evidence for non-overlapping predictors of growth in reading and mathematics. In studies of typically developing children, visual-spatial working memory may be a unique predictor for mathematics (Bull, Espy, & Wiebe, 2008; Holmes & Adams, 2006; LeFevre et al., 2010). This relation of visual-spatial working memory and math has been linked to the use of visual mental models in math problem solving. In young children, this may involve the manipulation of concrete objects or nonsymbolic quantities (Mix, Huttenlocher, & Levine, 2002; Rasmussen, Ho, & Bisanz, 2003). For older children, the use of mental models has been associated with better math word problem solving (Glenberg, Willford, Gibson, Goldberg, & Zhu, 2012) and with performance in domains of math that are typically encountered in the higher elementary and secondary school grades (Holmes, Adams, & Hamilton, 2008; Kytala & Lehto, 2008). Deficits in visual-spatial working memory have been found in adults with SBM (Iddon, Morgan, Loveday, Sahakian, & Pickard, 2004), but not in children (Mammarella, Cornoldi, & Donadello, 2007).

Fine motor and finger skills have also been linked uniquely to math in longitudinal studies (Noel, 2005). Some children with math difficulties have finger gnosis that is related to their word problem solving for small magnitudes (i.e., for numbers under 10; Costa et al., 2011),

and variability in finger gnosis as been specifically related to the use of fingers during counting and calculation in 5 to 7-year olds (Reeve & Humberstone, 2011). Because children use fingers across cultures for early counting and calculation (Butterworth, 1999), finger and number representations may co-develop such that areas of the brain responsible for the control of fine motor and finger movements become co-opted during development to support higher cognitive skills, namely, counting and calculation (Penner-Wilger et al., 2007). The use of fingers may also serve to “offload” some of the cognitive/memory load associated with making transformations (+ and –) on small numbers (Costa et al., 2011). SBM is associated with difficulties with fine motor skills including bimanual coordination (Lomax-Bream, Barnes, Copeland, Taylor, & Landry, 2007; Dennis & Barnes, 2010), and fine motor skills are significant unique predictors of nonverbal addition and subtraction problem solving in both typically developing preschoolers and in preschoolers with SBM (Barnes et al., 2011).

Cognitive correlates of mathematics may also vary with the type of mathematical skill being performed (LeFevre et al., 2010), strategy-use (Ansari & Dhital, 2006), and the age and skill level of the child, which might also reflect differences in strategy use (De Smedt et al., 2009; McKenzie, Bull & Gray, 2003; Meyer, Salimpoor, Wu, Geary, & Menon, 2009). Consistent with this idea that different math skills may be supported by different cognitive abilities, a study of mathematics in preschool children with SBM and their typically developing peers showed that at 60 months of age, after accounting for mathematical knowledge at 36 months of age, visual-spatial and fine motor skills uniquely predicted object-based quantity manipulation involving adding to and subtracting from hidden sets of objects in both groups. In contrast, phonological awareness and visual-spatial skill uniquely predicted oral counting (Barnes et al., 2011).

Although longitudinal studies of typically developing children and studies of children with MD suggest that several early cognitive abilities predict later math achievement, there are few studies that include a broad range of potential correlates such as phonological awareness, working memory, and fine motor skills; in particular, most studies have not looked at fine motor skills in the presence of these other cognitive correlates, and not in a longitudinal framework. As well, many longitudinal studies assess the impact of preschool cognitive abilities on later math achievement across fairly short developmental time windows of 2 or 3 years, often the prediction is to a broad test of mathematical achievement, and not all studies include both math and reading. When reading is assessed it is typically word decoding (but see Monette & Guay, 2011), even though mathematics and reading comprehension share the greatest phenotypic and etiological (genetic) overlap (Harlaar, Kovas, Dale, & Petrill, 2012), and may, therefore, be more likely to share common cognitive correlates than other aspects of reading. The current study addressed several of these issues by testing whether phonological awareness, working memory, and fine motor skills assessed between 36 and 60 months of age mediate differences in several aspects of later mathematics and reading achievement between typically developing children and those with SBM.

This study has three aims: 1) to test whether math-related cognitive abilities (phonological awareness, working memory, and fine motor/finger skills) measured in the preschool years (36 and 60 months) mediate the differences between children with and without SBM in mathematical achievement several years later, at 8.5–9.5 years of age; 2) to determine whether similar or different cognitive abilities in the preschool years mediate school-age outcomes in different aspects of math achievement, namely, single digit arithmetic fluency, single and multi-digit arithmetic calculations, and problem solving involving mathematical concepts; and 3) to determine whether cognitive abilities that mediate group differences in math outcomes are specific to math or whether they also account for group differences in

reading achievement, including reading decoding, reading fluency, and reading comprehension.

Based on studies reviewed above, we predict that cognitive abilities measured in the preschool years will partially mediate the effects of group on math achievement at school age. Specifically, given their role in counting and calculation, we expect that fine motor skills will be implicated in the models involving arithmetic (single and multi-digit calculation). Furthermore, given that multi-digit arithmetic involves both the holding and manipulation of partial answers and multiple steps and the retrieval of math facts and procedures from memory, both visual-spatial working memory and phonological awareness might also mediate group differences in calculation skills. Because math fluency requires the retrieval of math facts from memory and counting strategies for larger single digit problems we expect phonological awareness to serve as a mediator of math fluency performance. The test of quantitative concepts at this age consists of word problems, measurement problems, understanding of fraction concepts, and applied concepts such as money where the problems are supported by pictures. We predict that working memory might be implicated in these types of math problem solving. For reading, we predict that phonological awareness will mediate the effect of group on all aspects of reading. Although working memory might be predicted to mediate the effect of group for reading comprehension, a longitudinal study of inference-making and reading comprehension in children with SBM and in typically developing children (Pike et al., 2012) showed that working memory at 36 months is indirectly related to reading comprehension at 9–10 years of age through its influence on the ability to make inferences. We do not expect fine motor skills to be related to any aspect of reading.

Methods

Participants

This study is part of a longitudinal project on cognitive, motor, and social development in children with SBM and their typically developing peers in Ontario and Texas. Beginning in 1997, infants with SBM were identified by treating neurosurgeons and pediatricians in Houston (Memorial Herman Children's Hospital and Texas Children's Hospital) and southern Ontario (Toronto Hospital for Sick Children, McMaster Children's Hospital, Thames Valley Children's Centre), and were recruited into the study and examined several times between 6 months and 9–10 years of age. Detailed inclusion and exclusion criteria for the larger study can be found in Lomax-Bream et al., (2007). Exclusionary criteria included uncontrollable seizure disorders, other known congenital anomalies, and significant sensory impairments (blindness, deafness).

In the current study, children from the larger group of children with and without SBM were excluded if (1) they did not have complete data on mediator variables (56 were missing one mediator score); (2) their performance on more than one mathematical task was unreliable, typically due to significant child behavioral difficulties that affected test administration or incomplete test protocols if the child had to leave the assessment prior to completion (18 children); (3) they had global intellectual impairment (i.e., their scores on a nonverbal composite of Figure-Ground Relations and Form Completion from the Leiter International Performance Scale – Revised (Roid & Miller, 1997) and picture vocabulary from the WJ-III (Woodcock, McGrew, & Mather, 2001) were more than 2 standard deviations (*SD*) below the population mean at 8 years of age. Typically developing (TD) infants were recruited from advertisements in newspapers, local pediatricians, and from ads in hospital clinics serving children without neurodevelopmental or chronic medical disorders. Exclusionary criteria for this group included those above for the group with SBM, as well as no gross sensory or motor abnormalities.

The resulting sample contained 30 children with SBM and 35 with typical development. The subsample of children with SBM was compared to those children from the larger sample who were excluded for the reasons listed above. There were no differences in terms of gender, scores on measures of math calculation, $t(50) = -.62, p = .54$, and scores on word reading, $t(53) = -1.70, p = .10$. However, children with SBM included in the following analyses were from families of higher socioeconomic standing than those not included, $t(61) = -2.58, p < .05$.

The distribution of participants was relatively equal between the two sites. Most of the children with SBM had hydrocephalus treated with a diversionary shunt. Only 7 children had arrested hydrocephalus and no shunt. The majority of children with SBM had lower spinal lesions below LI (87 %).

Table 1 presents information on gender, ethnicity, and socioeconomic status by group. Socioeconomic status was assessed with the Hollingshead (1975) four-factor scale. The sociodemographics of the two sites differed because the Texas site included a greater number of children of Hispanic origin compared to the Ontario site. The TD group had a higher SES than the SBM group, $t(63) = -2.90, p < .01$. As a result, SES was entered as a covariate in all analyses. Groups differed in gender with more female participants in the group with SBM than in the TD group, $\chi^2(1) = 5.07, p < .05$; however, gender was not covaried as it was not associated with academic achievement outcomes. Table 1 shows that mean scores for verbal and nonverbal ability were in the average range for both groups.

Measures and Procedures

Participants were assessed between 3 and 4 hours depending on the assessment timepoint. Most participants were assessed at facilities associated with the project and some were assessed in their homes. Children tested in their homes were typically those who lived more than a 2 hour drive from the main performance sites. Families provided testing space that was quiet and interruptions were kept to a minimum. Breaks were provided as needed during testing, with more breaks needed at the 3-hour 36-month assessment point. Depending on the schedules of the families and other medical appointments that they might have been attending during the same visit, a small number of children were tested over two days. Consent was obtained from parents in accordance with the institutional review boards at the University of Texas Health Science Center at Houston and the Toronto Hospital for Sick Children for each assessment point, and assent was obtained from the children.

Math Measures—Three standardized measures were used to assess math learning and performance. The Calculation subtest of the Woodcock-Johnson Tests of Achievement - Revised (WJ-III; Woodcock & Johnson, 1989) evaluates mastery of mathematical computations, including single-and multi-digit addition, subtraction, multiplication, and division. These problems were solved using paper and pencil, with no imposed time limitation (median reliability of .85). The Math Fluency subtest of the WJ-III (Woodcock, McGrew, & Mather, 2001), a test of math fact mastery, assesses a child's ability to solve single-digit addition, subtraction, and multiplication problems, within a three-minute time limit (median reliability of .89). Calculation and Math Fluency were administered at the 9.5-year assessment.

The Stanford Binet IV Quantitative (Thorndike et al., 1989) assesses numerical reasoning and knowledge and application of numerical concepts, such as division, fractions, decimals, time, and measurement, using picture supports. This math task was administered at the 8.5-year assessment (reliability of .91 for this age).

Reading Measures—The Letter-Word Identification subtest of the WJ-III (Woodcock, McGrew, & Mather, 2001) is an untimed test of word decoding. Children are asked to read individual words of increasing complexity, from high frequency to low frequency (median reliability of .91).

On the Reading Fluency subtest from the WJ-III, children read short sentences of increasing complexity and circled yes if the statement was true and no if the statement was false within a three-minute time period (median reliability of .90). This measure assesses reading fluency and comprehension at the sentence-level.

The Passage Comprehension subtest from the WJ-III is a cloze reading exercise assessing reading comprehension. Items increase in difficulty by increasing passage length, level of vocabulary, and complexity of syntactic and semantic cues (median reliability of .83). All three reading measures were conducted at the 9.5-year assessment.

Cognitive Mediators—To measure fine motor skills, the Purdue Pegboard Test was used, and the number of rows completed using both hands was recorded. This task was administered at 36 months. Reported test-retest reliabilities for typically developing children range from .63–.82.

Phonological awareness was assessed at 60 months using a composite of Sound Matching and Elision from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, and Rashotte, 1999). Sound Matching measures the ability to choose the word (from pictures of 4 words) that contains a target sound tested in either the initial or final position in the word. For example, “What word starts with the same sound as *top*? *Pig, Tail, or Bat*?” (internal consistency of .93). Elision measures the ability to segment and manipulate sounds within words (internal consistency of .90). Earlier items require the child to delete part of a compound word such as ‘butter’ in ‘butterfly’; later items require the deletion of phoneme units to pronounce words (e.g., say “cup” without saying /k/).

Visual-spatial working memory was measured at 36 months using an experimental measure. The Six Boxes Task is a developmentally appropriate self-ordered pointing task assessing working memory/inhibitory control that requires the child to search for rewards in a group of six boxes. Rewards (e.g., cheerios) are hidden in the child’s view and then a screen is held up to cover the boxes from the child’s view for 5 seconds. The screen is removed and the child is allowed to search one box (1 trial) until all rewards are found (up to a maximum of 20 trials). The screen is used between each trial so that the child is required to wait 5 seconds between each search trial. Children are scored on the total number of searches required. This task requires the child to keep track of his or her history of searching multiple boxes for rewards (working memory) and to inhibit return to a previously rewarded location. Because the number of trials required varied from child to child, a split half method was used to estimate reliability, comparing odd numbered trials to the even numbered trials (reliability = .98).

Results

Math and Reading Group Comparisons

One-way ANCOVAs were conducted to examine group differences on math and reading outcomes, covarying for SES. Means are presented in Table 2. Children with SBM performed less well than their typically developing peers on math calculations, $F(1,62) = 27.63, p < .001, \eta^2 = .31$; math fluency, $F(1,60) = 11.62, p = .001, \eta^2 = .16$; and quantitative concepts, $F(1,62) = 3.97, p = .05, \eta^2 = .06$. While children with SBM performed comparably to TD peers on word decoding, $F(1,62) = 3.76, ns$; they were outperformed by TD peers on

reading fluency, $F(1,61) = 14.54, p < .001, \eta^2 = .19$, and passage comprehension, $F(1,62) = 12.18, p = .001, \eta^2 = .16$.

Mediation Analyses

The groups differed on the cognitive mediators, with the exception of the CTOPP Sound Matching subtest. Bivariate correlations between potential cognitive mediators and math outcomes are presented in Table 3. Analyses of mediation effects used a multiple mediation model (Preacher & Hayes, 2008) to simultaneously assess multiple early abilities as potential mediators (fine motor skills, visual-spatial working memory, and phonological awareness) for the effect of group (SBM versus TD peers) on math outcomes, covarying for SES. Mediation analyses were also conducted for reading outcomes so that the specificity of the potential mediators could be examined. Multiple mediator models have several advantages over multiple, simple mediation models, including more accurate parameter estimates, comparison of indirect effects in the context of others, as well as allowing for assessment of the combined effect of all mediators (i.e., the total indirect effect). Following the recommendations by Preacher and Hayes (2008), a bootstrapping sampling procedure was applied for assessing indirect effects. Bootstrapping is a nonparametric resampling procedure where a large number of samples (5000 in the current study) are drawn with replacement from the full data set. Based on these samples, approximations of the distribution of the indirect effects are obtained and point estimates and confidence intervals calculated.

According to Preacher and Hayes (2008), the bootstrapping procedure is superior to other approaches to mediation including the product of coefficients approach or the Sobel test as well as the commonly used causal steps approach outlined in Baron and Kenny (1986) in terms of statistical power while maintaining reasonable control over the Type I error rate. Additionally, bootstrapping is recommended when the assumption of normality of the sampling distribution is questionable, as may be the case in small samples. In the present study, the bootstrapping procedure was conducted using the SPSS macro provided by Preacher and Hayes. A point estimate for an indirect effect was considered significant when the bias corrected and accelerated (BCa) confidence interval did not include zero.

Mathematical Achievement Measures—The multiple mediation models for the three math tasks are in Figures 1a, b, and c. For math calculations, the total indirect effect for this set of mediators was significant with a point estimate of 10.10 and a 95% BCa bootstrap CI of 4.32 to 20.00, indicating that at least one of the variables significantly mediated the effect of group on math calculations. Math calculations were predicted quite well from group, phonological awareness, visual-spatial working memory, and fine motor skills, with Adjusted $R^2 = .62, F(5, 58) = p < .001$. An examination of the specific indirect effects showed that visual-spatial working memory and phonological awareness were significant mediators, with point estimates of 4.96 and 2.50 and 95% CIs of 2.04 to 12.67 and .02 to 7.88. With all mediators entered in the model, the direct effect from group to math calculation remained significant $b = 16.87, t = 3.91, p < .001$.

The total indirect effect of group on math fluency through the set of proposed mediators was significant with a point estimate of 4.06 and a 95% BCa bootstrap CI of .97 to 8.32. Group and the proposed set of mediators accounted for a significant proportion of variation in math fluency, Adjusted $R^2 = .32, F(5, 56) = 6.64, p < .001$. However, only phonological awareness was shown to significantly mediate the effect of group on math fluency, with a point estimate of 1.92 and a 95% CI of .80 to 5.57. The direct effect of group on math fluency with all mediators in the model remained statistically significant $b = 7.64, t = 2.14, p < .05$.

For quantitative concepts, the total indirect effect was significant with a point estimate of 4.58 and a 95% BCa bootstrap CI of .03 to 10.16. The independent variable and proposed mediators accounted for a small but significant portion of the variation in quantitative concepts, Adjusted $R^2 = .13$, $F(5, 58) = 2.91$, $p < .05$. Visual-spatial working memory emerged as the only significant mediator, with a point estimate of 2.17 and a 95% CI of .25 to 6.41. With all mediators in the model, the direct effect of group on quantitative was no longer significant $b = 4.35$, $t < 1$, $p = .35$.

Reading Achievement Measures—For the reading outcomes, reading fluency and passage comprehension were examined, as group differences were not observed on word decoding. The total indirect effect of group on reading fluency and passage comprehension through the set of mediators was significant, with point estimates of 4.14 and 6.10; and 95% CIs of .83 to 8.95, and 1.77 to 14.12, respectively. The independent variable and proposed set of mediators accounted for a significant proportion of the variation in reading fluency (Adjusted $R^2 = .40$, $F(5, 57) = 9.27$, $p < .001$) and passage comprehension (Adjusted $R^2 = .46$, $F(5, 58) = 11.83$, $p < .001$). In comparison to math outcomes, phonological awareness emerged as the only significant mediator of the group on reading fluency (point estimate = 3.05, 95% CI = .56 to 7.51) and passage comprehension (point estimate = 4.37, 95% CI = .73 to 9.69). With all mediators in the models, the direct effects of group on reading fluency ($b = 9.50$, $t = 2.84$, $p < .01$) and passage comprehension ($b = 8.51$, $t = 2.25$, $p < .05$) remained significant. The model for passage comprehension is in Figure 2.

Discussion

This longitudinal study used a neurodevelopmental disorder, SBM, that is associated with well-developed word reading, but learning difficulties in mathematics to investigate whether a number of math-related cognitive abilities in the preschool years mediate differences between children with SBM and their typically developing peers in math achievement 4 to 6 years later. The study is unique because: 1) it assessed whether there is any impact of early developing cognitive abilities on school-age math achievement over a longer developmental window than has been previously studied; 2) it simultaneously tested several hypothesized math-related cognitive correlates on a variety of mathematical outcomes; and 3) it assessed the specificity of these cognitive correlates by testing whether they also accounted for group differences in reading fluency and comprehension.

We found that early measured cognitive abilities mediated later group differences in some aspects of math, but that the specific correlates of later mathematical achievement varied according to the type of mathematical task, and only phonological awareness mediated group differences in both academic domains. Although mediation models cannot provide evidence of causality, time precedence in this study provides relatively stronger evidence than other types of correlational and mediation studies. Here, the fact that cognitive variables assessed in the preschool years continued to have a significant effect on academic outcomes measured 4 to 6 years later, suggests that these early cognitive abilities are important for supporting later mathematical learning and performance. The implications for mathematical cognition, development, and interventions are discussed below.

The mediation models showed that for problems combining single and multi-digit calculations phonological awareness and visual-spatial working memory significantly and uniquely mediated the group difference in calculation. Phonological representations are related to direct retrieval of small arithmetic problems (i.e., sums or minuends of 10 or less) from memory (De Smedt et al., 2010), and phonological awareness in preschool and kindergarten is a strong unique predictor two years later of a variety of mathematical outcomes, including numeration and calculation (LeFevre et al., 2010). Our findings suggest

that the quality of preschool phonological representations are linked to individual differences in mathematical knowledge and performance in the area of calculations well into the middle elementary grades.

Visual-spatial working memory was also a significant mediator of calculation, consistent with findings from other longitudinal studies that followed 4–5 year old children across two years of school (Bull et al., 2008; LeFevre et al., 2010). Working memory is important for the holding of the partial products of calculation procedures during multi-step problem solving; however, verbal working memory has been implicated to a greater extent than visual-spatial working memory in studies of calculation in school-age children with and without MD (e.g., Geary et al., 2007; Swanson & Jerman, 2006). Verbal and visual-spatial working memory systems show less differentiation before 8 years of age than in older children and adults (Hale, Bronik, & Fry, 1997); our nonverbal measure of working memory at 36 months of age may tap the early development of this relatively undifferentiated working memory system. Importantly, it is the integrity of the working memory system quite early in life that uniquely predicts calculation skills much later in development.

Fine motor skills have been assessed in only a few longitudinal studies, and typically not in the presence of other cognitive correlates of math. Finger gnosis at the beginning of first grade uniquely predicts performance on a variety of mathematical tasks, but not reading, a year later (Noel, 2005), finger gnosis is associated with the use of fingers to calculate in 5 to 7 year-olds (Reeve & Humberstone, 2011), and finger training in first grade improves performance on some mathematical tasks (Gracie-Bafalluy & Noel, 2008). In both typically developing children and children with SBM, fine motor skill is a unique predictor of early nonsymbolic addition and subtraction at 5 years of age (Barnes et al., 2011). The current study, however, showed that early variability in fine motor skills did not mediate the effect of group on either later mathematical calculations or single digit arithmetic. It is noteworthy that the children in the current study are several years older than those in other studies showing contributions of fine motor skills or finger gnosis to arithmetic. The role of finger or fine motor skills in calculation may be developmentally limited such that it lessens over time as children come to rely more on direct retrieval of arithmetic facts from memory than on finger counting strategies. Measurement of the use of finger counting strategies on the math tasks might have helped to provide support for this hypothesis. Alternatively finger gnosis, may be more sensitive for measuring those finger abilities that are most strongly tied to calculation than the speeded fine motor dexterity task used in the present study (Penner-Wilger et al., 2007; Reeve & Humberstone, 2011).

Of interest is the finding that by age 9.5, group differences in math fact retrieval were mediated only by phonological awareness. Phonological awareness has been found to mediate individual differences in direct retrieval of answers to small addition problems, suggesting that it is the ability to make fine-grained phonological differentiations that supports the transition from counting strategies to direct retrieval of small arithmetic facts in memory (De Smedt et al., 2009). Although the math fluency test has small and large addition problems as well as multiplication problems, most of the items that children between 9 to 10 years of age would be expected to complete (the first 50–60 items), are small addition problems (sums below 10) and small subtraction problems (minuends of 10 or less). An experimental measure of math fact fluency that specifically manipulated small and large problem size and type of operation might provide better information about the potential range of developmental precursors that might underlie later performance on single digit arithmetic.

For children in the middle elementary school grades, the math problem solving task that we used consists of word problems, measurement problems and applied problems involving

money concepts, with most problems partially supported by pictorial information. Visual-spatial working memory mediated the effect of group. Working memory has been implicated in math problem solving in some studies over and above arithmetic skills, reading skills, short term memory, and intelligence (Swanson & Beebe-Frankenberger, 2004; but see Fuchs et al., 2006). The current findings suggest that early variability in the working memory system measured in the first 36 months of life is a significant mediator of later math problem solving. We do not think that these findings are specific to the type of math problem solving task that was used (i.e., with supporting pictures) given that visual-spatial aspects of working memory also play a greater role in math word problem solving with increasing age (Meyer et al., 2010). The fact that this mediation model accounted for less variance than the models for math fluency and calculations suggests that other abilities we did not assess early in development are important for later math problem solving.

This study also showed that the early developmental precursors of reading overlap with those for some, but not all, aspects of mathematics. Consistent with previous studies, children with SBM did not differ from their peers on reading words, but they differed in reading fluency/comprehension at the sentence level and passage-level reading comprehension. Reading and mathematical abilities and disabilities have a high degree of overlap in behavioral and genetic studies (Plomin & Kovas, 2005) with recent studies suggesting the strongest links are between mathematics and reading comprehension (Harlaar et al., 2012). We suggest that some of this overlap in reading decoding, reading comprehension and mathematics may be related to common phonological processes that underlie performance in both academic domains. The quality of phonological representations appears to be important for math calculations and single digit arithmetic fluency as well as for reading fluency and comprehension. Other potential common cognitive correlates for mathematics and reading comprehension such as working memory were not found in this study. As mentioned earlier, 36-month visual-spatial working memory has been linked to later reading comprehension, but only indirectly through its influence on the ability to make inferences that integrate information within text (Pike et al., 2012). We could not measure verbal working memory at 36 months and did not measure it at 60 months. Had we done so, verbal working memory abilities at 5 years of age might have mediated the effects of group for both mathematics and reading comprehension.

Limitations and Implications

Recent studies suggest that both domain specific (i.e., number sense including large number acuity and ability to subitize) and domain general (e.g., working memory) abilities contribute to explaining mathematical development and disability (e.g., LeFevre et al., 2010; Mazzocco, Feigenson, & Halberda, 2011a, 2011b; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011). There is some inconsistency in the literature as to whether the effects of domain specific number abilities are only for symbolic (Holloway & Ansari, 2009) or for both symbolic and nonsymbolic number (Mazzocco et al., 2011). Although we tested mediation with several cognitive abilities, we did not include a measure of early number sense. It is possible that both early domain specific and domain general abilities uniquely contribute to later mathematical performance. It is also possible that a domain general ability such as working memory affects later mathematics achievement indirectly through its influence on early number abilities (e.g., Östergren & Träff, 2013). These questions were beyond the scope of the current study.

Furthermore, we were not able to test the entire range of preschool executive and self-regulatory functions that have been related to math and reading in the early school years (Blair & Razza, 2007; Bull et al., 2008), though we did choose the one – working memory – that is consistently shown to be related to mathematical processing. In particular, several studies show the importance of the Central Executive (CE) in mathematical performance

and learning. Dual task studies with adults suggest that the CE plays a significant role in single and multi-digit arithmetic performance (reviewed in LeFevre, DeStefano, Coleman, & Shanahan, 2005). Longitudinal studies show that CE functioning in the preschool years, tapped by measures of inhibition and switching, predict better school readiness in both math and reading and remain strong predictors of academic performance across the first three years of school (Bull et al., 2008). And, measures of the CE (complex working memory tasks with a dual task component) mediate group differences in math for children with and without math learning disabilities (Geary et al., 2007). Whether some of the results obtained in the current study would change if preschool measures of CE functioning had been included in the mediation models is unknown, but warrants further exploration.

Finally, at 36 months, developmentally appropriate working memory paradigms are nonverbal in nature (Garon, Bryson, & Smith, 2008) and often do not permit one to discriminate updating and storage functions from inhibitory control functions of working memory. Therefore, it is not possible to determine what aspects of working memory and attentional control account for the mediation effects for calculation and math problem solving.

When early cognitive difficulties are found to contribute to a later developing academic skill it is tempting to think about early interventions for children at risk that focus on these cognitive precursor skills. To date, most studies that train cognitive skills such as working memory and measure effects on academic outcomes have been conducted with school-age children. A recent meta-analysis found no evidence for transfer from working memory training to academic outcomes (Melby-Lervag & Hulme, 2012); however, there are several unanswered questions about the utility of cognitive training for academic skill development. One is whether training of general cognitive systems that support learning might be more effective at younger ages when the neural systems underlying these aspects of cognition are still relatively undifferentiated and unspecialized (reviewed in Wass, Scerif, & Johnson, 2012). Another question has to do with the approach to training of domain general cognitive abilities, which might have implications for transfer to academic skill learning. The effectiveness of interventions for both younger and older students that combine specific academic skills training with domain general cognitive training or that train cognitive abilities through the use of relevant domain specific materials to address issues of transfer is largely unknown.

In conclusion, the findings of this study suggest that there are multiple pathways that contribute to different aspects of mathematical performance (LeFevre et al., 2010). Some of these, such as visual-spatial working memory, are unique to mathematics while others, such as phonological awareness, are implicated in the development of both mathematics and reading. Even within the domain of mathematics, there is evidence that different developmental precursors are associated with different mathematical skills. Finally, this study provides evidence for the importance of the effects of early developmental processes on later mathematical achievement well into the middle elementary grades.

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Children with spina bifida and typical peers followed from 36 months to 9.5 years.
Longitudinal mediation models tested cognitive precursors of math and reading.
Visual-spatial working memory was related to math calculations and problem solving.
Phonological awareness mediated math fluency, calculation, and reading.
Findings have implications for models of math development and disability.

a.

b.

Figure 1.

a. Multiple mediation of math calculations: (a) path estimates for the total effect of group on math calculations (controlling for SES); and (b) the direct effect of group on math calculations independent of the pathways through the proposed mediators (phonological awareness, visual-spatial working memory, and fine motor skills).

*= $p < .05$; **= $p < .01$

b. Multiple mediation of math fluency: (a) path estimates for the total effect of group on math fluency (controlling for SES); and (b) the direct effect of group on math fluency

independent of the pathways through the proposed mediators (phonological awareness, visual-spatial working memory, and fine motor skills).

*= $p < .05$; **= $p < .01$

c. Multiple mediation of quantitative: (a) path estimates for the total effect of group on quantitative (controlling for SES); and (b) the direct effect of group on quantitative independent of the pathways through the proposed mediators (phonological awareness, visual-spatial working memory, and fine motor skills).

*= $p < .05$; **= $p < .01$

Figure 2.

Multiple mediation of passage comprehension: (a) path estimates for the total effect of group on passage comprehension (controlling for SES); and (b) the direct effect of group on passage comprehension independent of the pathways through the proposed mediators (phonological awareness, visual-spatial working memory, and fine motor skills).

*= $p < .05$; **= $p < .01$

Table 1

Descriptive information on spina bifida and control groups

	Spina Bifida (<i>n</i> = 30)	Control (<i>n</i> = 35)
Sex (female)	73 %	46%
Hollingshead SES *	35.72	45.80
Ethnicity		
African American	13%	3%
Caucasian	60%	69%
Hispanic	23%	20%
Other	3%	8%
WJ-R Picture Vocabulary *	102.37	114.14
Nonverbal Composite**	9.30	12.43
Purdue Pegs *	1.33	2.29
6 Boxes Task *	9.73	7.43
CTOPP Elision *	8.43	10.14
CTOPP Sound Matching	9.53	10.40
Phonological Awareness Composite *	8.98	10.27

Note.

* denotes a significant group difference. Values are standard scores except for Purdue Pegs which was number of rows completed, and 6 Boxes which was number of searches. WJ-R = Woodcock-Johnson Test of Cognitive Abilities – Revised; Nonverbal Composite = Figure Ground and Form Completion from the Leiter International Performance Scale – Revised; CTOPP = Comprehensive Test of Phonological Processing; Phonological Awareness Composite = CTOPP Elision and CTOPP Sound Matching.

Table 2

Math and reading outcomes for spina bifida and control groups

	Spina Bifida			Control		
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>
WJ-III Math Calculations	30	84.97	20.31	35	113.74	18.01
WJ-III Math Fluency	28	86.25	12.66	35	99.86	13.24
SB-IV Quantitative	30	94.33	12.56	35	104.40	19.13
WJ-III Letter-Word ID	30	103.80	20.87	35	117.51	16.09
WJ-III Reading Fluency	29	91.10	13.37	35	105.94	12.61
WJ-III Passage Comprehension	30	100.80	18.39	35	118.03	12.79

Table 3

Bivariate Correlations between potential cognitive mediators and math outcomes

	Fine motor	VSWM	Phonological Awareness
Math Calculations	.48**	-.56**	.53**
Math Fluency	.32**	-.28*	.46**
Quantitative	.27*	-.32*	.33**

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