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# Neurocognitive Predictors of Mathematical Processing in School-Aged Children with Spina Bifida and Their Typically Developing Peers: Attention, Working Memory, and Fine Motor Skills

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## Abstract

**Objective—**Math and attention are related in neurobiological and behavioral models of mathematical cognition. This study employed model-driven assessments of attention and math in children with spina bifida myelomeningocele (SBM), who have known math difficulties and specific attentional deficits, to more directly examine putative relations between attention and mathematical processing. The relation of other domain general abilities and math was also investigated.

**Method—**Participants were 9.5-year-old children with SBM ($N$ = 44) and typically developing children ($N$ = 50). Participants were administered experimental exact and approximate arithmetic tasks, and standardized measures of math fluency and calculation. Cognitive measures included the Attention Network Test (ANT), and standardized measures of fine motor skills, verbal working memory (WM), and visual-spatial WM.

**Results—**Children with SBM performed similarly to peers on exact arithmetic but more poorly on approximate and standardized arithmetic measures. On the ANT, children with SBM differed from controls on orienting attention but not alerting and executive attention. Multiple mediation models showed that: fine motor skills and verbal WM mediated the relation of group to approximate arithmetic; fine motor skills and visual-spatial WM mediated the relation of group to math fluency; and verbal and visual-spatial WM mediated the relation of group to math calculation. Attention was not a significant mediator of the effects of group for any aspect of math in this study.

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**Conclusions—**Results are discussed with reference to models of attention, WM, and mathematical cognition.

SBM offers a powerful model for studying the cognitive correlates of math difficulty for several reasons. First, number deficits in SBM are domain-specific, in that individuals with SBM reliably show stronger reading than math across the lifespan (Ayr, Yeates, & Enrile, 2005; Dennis & Barnes, 2002; Fletcher et al., 2005). Second, difficulties in aspects of math fact retrieval and multi-digit arithmetic processing in this population are similar to those of neurologically intact children with math disability (Barnes et al., 2006). Third, children with SBM have deficits in several skills associated with math difficulties in typically developing populations (Cirino, Fletcher, Ewing-Cobbs, Barnes, & Fuchs, 2007; Noel, 2005; Raghubar, Barnes, & Hecht, 2010), including attention (Dennis, Landry, Barnes, & Fletcher, 2006), working memory (Mammarella, Cornoldi, & Donadello, 2003), and fine motor skills (Lomax-Bream et al., 2007). However, most studies do not: consider all of these hypothesized correlates of mathematical processing in one study; use assessments of cognitive and mathematical processing that are derived from cognitive models of these skills; study the relation of these cognitive correlates to different aspects of math; and test whether these cognitive correlates account for the group differences in mathematical performance. The current study addresses these issues.

## Mathematical Processing in Children with SBM

As early as 36 and 60 months of age, preschoolers with SBM demonstrate difficulties with early numeracy skills including knowledge of counting principles, producing the counting string, and object-based arithmetic for sums and subtrahends of 4 and greater (Barnes et al., 2011). School-aged children with SBM, are less skilled at single-digit arithmetic, where they employ direct retrieval of math facts from memory less often and counting strategies more often than their typically developing peers (Barnes et al., 2006), a pattern similar to that in neurologically normal children with math disabilities (Geary, Hamson, & Hoard, 2000; Jordan, Hanich, & Kaplan, 2003). Error coding studies for multi-digit arithmetic among children with SBM suggest less well-developed knowledge of concepts and procedures, such as regrouping; these children commit more procedural errors than same-age peers (Ayr et al., 2005; Barnes et al., 2002; 2006), like children with math difficulties (Raghubar et al., 2009). These difficulties in math persist into adulthood, with consequences for functional numeracy and independence (Dennis & Barnes, 2002).

Whether and how difficulties in domain general attention, working memory and/or fine motor skills are related to arithmetical processing at school age is largely unknown. Further, little is known about approximate arithmetic in children and adults with SBM, but it is an area of interest given that the posterior brain regions implicated in approximate arithmetic or estimation (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999) are abnormal in this population.

## Neurocognitive Predictors of Math

Attention is required to monitor the sequence of steps of an algorithm, detect and correct errors, suppress irrelevant information, and inhibit competing responses. Not surprisingly, math disabilities and attention disorders often co-occur (Fletcher, 2005; Shalev, Auerbach, Manor, & Gross-Tsur, 2000; Zentall, 2007), and teacher ratings of school-aged children's inattention are highly predictive of math achievement and specific math skills (Cirino et al., 2007; Fuchs et al., 2006; Raghubar, et al., 2009).

Understanding how attention and math are related requires articulated models of each. The Posner model (e.g., Fan, McCandliss, Sommer, Raz, & Posner, 2002) proposes three attention networks: an *alerting network*, important for sustaining attention over time; an *orienting network*, important for moving and shifting attention; and an *executive network*, important for voluntary control of attention and response inhibition as well as monitoring. The Attention Network Test (ANT; Fan et al., 2002), based on Posner's model, is most often used to study developmental and individual differences in the operation of these attention networks.

The relation between attention networks and math is ripe for further investigation, and children with SBM provide a good investigative population. Although individuals with math difficulties have problems with executive attention (e.g., Geary, 2004), there is limited information about dyscalculia and each of the three networks. On the one hand, a study using the ANT revealed impairments in alerting and executive systems but not in orienting attention in adults with dyscalculia (Ashkenazi & Henik, 2010). On the other hand, posterior brain regions underlying orienting attention have also been implicated in mathematical processes, such as number comparison, approximation, subtraction, and counting in adults (Dehaene, Piazza, Pinel, & Cohen, 2005).

While children with SBM have an elevated rate of parent-reported attention problems (Burmeister et al., 2005), they are rarely hyperactive (Fletcher et al., 2005). Moreover, they have relatively better executive attention than orienting attention (Dennis et al., 2006; Taylor et al., 2010; reviewed in Dennis, Sinopoli, Fletcher, & Schachar, 2008), and they perform as well as controls on tasks of executive attention involving restraint inhibition (i.e., Go/No Go tasks; Ou, Snow, Byerley, Hall, & Glasier, 2013; Vinck, Mullaart, Rotteveel, & Maassen, 2009). In short, children with SBM have difficulties in attention orienting, the neuroanatomy of which has been implicated in some math skills, although they do not appear to have executive attention deficits, which have been implicated in dyscalculia in adults and related to the development of both reading and math in young children (Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008).

## Working Memory

Verbal working memory, which supports encoding, retention, and manipulation of verbal codes used for counting, exact arithmetic, and mathematical algorithms (Dehaene et al., 1999; 2005), is related to math achievement in school-aged children (Raghubar et al., 2010) and commonly distinguishes children with math difficulties from typically developing peers (e.g., Fuchs et al., 2008; Mabbot & Bisanz, 2008; Swanson & Jerman, 2006). How verbal working memory facilitates math performance continues to be debated (review in Raghubar et al., 2010).

Visual spatial working memory may aid the formation of mental models, thereby promoting mastery of informal math skills, such as object-based inversion problems and addition and subtraction problems in younger children (e.g. an examiner places two disks on a mat, covers the display, slides 2 more disks behind the screen and asks the child to replicate what is on the examiner's mat – a 2+2 problem) (e.g., Bisanz, Sherman, Rasmussen, & Ho, 2005; Huttenlocher, Jordan, & Levine, 1994; Klein & Bisanz, 2000). Mental models may also be used by older children to facilitate performance on more complex mathematical tasks including word problem solving (Glenberg et al., 2012; Holmes & Adams, 2006; Holmes, Adams, & Hamilton, 2008; Raghubar et al., 2010; Reukhala, 2001).

The relation between working memory and math in children with SBM is understudied. Verbal working memory deficits in adults with SBM are related to their computation abilities (Dennis & Barnes, 2002). One study of working memory in children with SBM reported a deficit in visual-spatial working memory at 36 months of age (Barnes et al., 2014), which partially mediated the effect of group on calculation and math problem solving at school-age. Another study described a deficit in visual (but not spatial) working memory at school age (Mammarella et al., 2003).

### Fine Motor Skills

Throughout the lifespan, individuals with SBM exhibit a broad range of motor deficits including poor fine motor functioning, motor planning, and fine motor speed (Fletcher, Brookshire, Bohan, Brandt, & Davidson, 1995; Hetherington & Dennis, 1999). In typically developing populations, finger localization/gnosis predicts performance on standard mathematical tests, including number system knowledge and calculation (Noel, 2005; Penner-Wilger et al., 2007) as well as tasks tapping numerical representations, such as number-line estimation and magnitude comparison (Penner-Wilger et al., 2008). Other fine motor skills such as finger tapping speed are also predictive of number system knowledge (Penner-Wilger et al., 2007). Such findings have been have been used to argue for common neural representations of fingers and numbers because of their functional co-developmental connections through the use of fingers to count and calculate (Butterworth, 1999).

Among 60-month-old children with SBM and their typically developing peers, fine motor skill predicts object-based arithmetic, but not performance on conceptual and procedural counting tasks, suggesting some specificity in non-symbolic arithmetic tasks (i.e., those involving mathematical manipulation of concrete objects) in the preschool years (Barnes et al., 2011). Whether fine motor skills are related to either exact and/or approximate arithmetic in school-age children with SBM is unknown.

## The Present Study

This study investigates whether math-related cognitive abilities predict group differences in specific math skills, including experimental measures of exact and approximate arithmetic, and standardized measures of single-digit arithmetic fluency and single- and multi-digit calculation. We had three specific aims:

1. To report mathematical processing and achievement, including a direct comparison of exact versus approximate arithmetic, in 9.5-year-old children with SBM and typically developing children. We hypothesized that children with SBM would score lower than their peers on all math outcomes.
2. To report attention, working memory, and fine motor skill in school-age children with SBM and their typically developing peers. We hypothesized that children with SBM would perform more poorly on measures of attention orienting, working memory and fine motor skill, although not on measures of executive attention.
3. To examine whether group outcome differences in math are associated with differences in attention, working memory, and fine motor skills. In particular, we examined whether specific neurocognitive abilities mediate group differences on specific math outcomes using multiple mediation models.

# Method

## Participants

This study is part of a longitudinal project on cognitive, social, and motor development in children with spina bifida in Toronto, Ontario and Houston, Texas. Starting in 1997, infants with spina bifida ($N$ = 91) were identified by neurosurgeons and pediatricians and recruited into the study. All children with spina bifida were born with the most common and severe type of spina bifida, meningomyelocele (SBM). Age-matched typically developing children ($N$ = 74) were recruited from well-baby clinics and community advertisements. Children were assessed several times between 6 months and 9 years of age.

Inclusion criteria from the longitudinal study were: (1) absence of uncontrollable seizure disorders, other known congenital anomalies outside of SBM (though children SBM with associated neurological anomalies, such as Arnold Chiari II malformation and hydrocephalus were included), and significant sensory impairments, such as blindness or deafness; (2) gestational ages from 34 to 41 weeks; (3) birth weight appropriate for gestational age; (4) a normal history of pregnancy and birth; (5) Apgar score at 5 min of 8 or greater; (6) and normal physical examination. The same inclusionary criteria applied to typically developing children as well as a lack of gross sensory or motor disabilities. For this study, 41 children with SBM and 22 typically developing children were lost to follow-up. Those lost to follow-up did not differ from those who remained in the study with respect to proportion of children with hydrocephalus requiring shunting [$\chi^2(1) = <1$, $p = .56$] and lower versus higher level lesions [$\chi^2(1) = <1$, $p = 1.0$], and socioeconomic standing [$t(83) = -.24$, $p = .81$. For this particular study, children were excluded if they had intellectual impairment (i.e., their scores on both Picture Vocabulary from the Woodcock-Johnson III Tests of Cognitive Abilities (Woodcock, McGrew, & Mather, 2001a) and Figure-Ground Relations from the Leiter International Performance Scale – Revised (Roid & Miller, 1997) were more than 2 standard deviations below the population mean at 9 years of age) and they did not have complete data on mediator variables (6 children with SBM and 5 typically developing children). The sample consisted of 44 children with SBM and 50 typically developing children.

The distribution of participants was similar between the two sites. Most children with SBM had hydrocephalus, subsequently treated with diversionary shunt (87%); the remaining children had arrested hydrocephalus and no shunt. Ninety-five percent of children with SBM had lower level spinal lesions, below T12. Consent was obtained from parents in accordance with institutional review boards at the University of Texas Health Science Center at Houston and The Hospital for Sick Children in Toronto.

Table 1 illustrates the distributions of participant gender, ethnicity, and socioeconomic status (SES), as assessed by the Hollingshead (1975) four-factor scale. The sociodemographics of the Texas and Ontario sites differed because the Texas site included more Hispanic children. The typically developing group had a higher SES than the group with SBM [$t(100) = 4.90$, $p < .001$], reflecting the greater proportion of economically disadvantaged Hispanic children with SBM in Texas. As a result, analyses involving group comparisons include SES as a covariate. The groups differed on gender, with more female participants in the group with SBM than in the typically developing group [$\chi^2(1) = 4.04$, $p < .05$]. Gender was not used as a covariate because it was not associated with math outcomes in this sample ($p$-values > .05).

## Measures

**Experimental arithmetic measures—**The experimental math tasks assessed exact arithmetic and approximate arithmetic (e.g., Dehaene et al., 1999) on a laptop computer. Each trial began with the presentation of a fixation point (*****) in the middle of the screen for 1500 ms, followed by a blank screen for 250 ms, and then the arithmetic problem. Problems were presented in random order in a horizontal format (3 + 4) in the center of the screen, with the 2 answer choices below on the right and left sides. Participants were instructed to press a response key (Z on the left side, / on the right) as quickly and accurately as possible. Responses were timed from the onset of the problem screen to the onset of the response, at which point the problem disappeared from the screen. Following each arithmetic problem, a blank screen was presented for 250 ms. Feedback was only provided following the practice trials. For accuracy data, the proportion of correct responses was recorded. Response time data were cleaned such that response times of 100 ms or less were excluded as pre-pushes. The median correct response latency for each participant was recorded for each task.

**Exact Arithmetic Task:** This task consisted of 24 single-digit addition problems, with addends and augends ranging from 2 to 9. Tie (e.g., 2+2) and inverse problems (3+2 and 2+3) were excluded as well as problems involving the numbers 0 and 1. The stimulus set consisted of 10 small size problems (answer is 10 or less) and 14 large size problems (answer is greater than 10). Each addition problem was accompanied by 2 answer choices: the correct answer and a false answer equal to the correct answer plus or minus 1.

**Approximate Arithmetic Task:** This task was composed of 4 practice trials followed by 20 single-digit arithmetic problems, with addends and augends ranging from 2 to 9. Similar to the exact arithmetic task, tie and inverse problems, as well as those containing the numbers 0 or 1 were excluded. The stimulus set consisted of 6 small size problems and 14 large size problems. Each problem was accompanied by two answer choices that were within +/− 3 of each other. Participants were instructed to make their best guess about which number was closer to the correct answer.

## Standardized arithmetic measures

**Calculation:** The Calculation subtest of the Woodcock-Johnson Tests of Achievement – Third Edition (WJ-R; Woodcock & Johnson, 1989) evaluates mastery of mathematical computations, including single- and multi-digit addition, subtraction, multiplication, and division. The number of correctly calculated problems was recorded and converted to a standard score. This measure has excellent reliability, $r = .93$) (Reviewed in Woodcock, 1990).

**Math fluency:** The Math Fluency subtest of the WJ-III (Woodcock, McGrew, & Mather, 2001b), a test of math fact mastery, assesses a child's ability to rapidly and accurately solve single-digit addition, subtraction, and multiplication problems, within a three minute time limit. The number of problems solved correctly within the time period was recorded and converted to a standard score. Math fluency has excellent reliability, $r = .90$ (McGrew & Woodcock, 2001).

## Cognitive predictors

**Attention:** A modified Child Attention Network Test (ANT) (Rueda et al., 2004) assessed attention. Although reliability estimates are not available for the child version of the ANT, split-half reliability for the adult version is low to moderate for both the accuracy and response time subtractions (MacLeod et al., 2010).

A single yellow fish or a horizontal row of five yellow fish was presented above or below a fixation point against a blue-green background. The target was a centered leftward or rightward pointing fish. On *congruent trials*, the flanking fish pointed in the same direction as the central fish; on *incongruent trials*, the central fish pointed in the opposite direction; and on *neutral trials*, the central fish appeared alone. The participant's task was to identify the direction of the centrally presented fish by making a keyboard press of Z for the left direction or / for the right direction.

After a random variable duration fixation period (400–1600 ms), a warning cue was presented for 150 ms, followed by a second fixation period of 450 ms. Then either the target and flanker appeared together, or the target appeared alone, and remained on the screen until a response was detected, or until 1700 ms had passed (Fan et al., 2002; Rueda et al, 2004). Trials with a response time greater than 1700 ms were excluded from analyses (<2 percent of all trials). Feedback ("Correct" or "Incorrect") was given only during practice trials.

To measure alerting and/or orienting, there were four warning conditions: no cue, center cue, double cue, and spatial cue (see Figure 1). For the no cue trials, participants saw only a fixation for 150 ms. For the center cue trials, participants were shown a black hollow square surrounding the black fixation cross. For the double cue trials, two smaller squares appeared at the locations of the target, above and below the fixation cross. For the spatial cue trials, a square was presented at the position of the upcoming target.

Stimuli were presented on a lap top computer, and children viewed the screen from a distance of about 40 cm with their head in a chinrest. A session consisted of 24 practice trials and 96 experimental trials. Each trial represented one of 12 conditions in equal proportions: three target types (congruent, incongruent, and neutral) x four cues (no cue, central cue, double cue, and spatial cue). Targets appeared twice on the left side and twice on the right side for each condition in each block.

Accuracy and median response time data were collected for each attention network. For response time data, only valid trials (correct response >100 ms and <1700 ms) were included. For *alerting attention*, cue type was examined across flanker condition, with no cue versus double cue being the comparison of interest. The double cue median response time was subtracted from the no cue median response time for each subject, and the means of these subtracted medians compared. *Orienting attention* was also assessed by examining cue type across flanker condition, but with center cue versus spatial cue being the comparison of interest, as well as by subtracting the spatial cue median response time from the center cue median response time, and comparing the means of the subtracted medians. *Executive attention* was measured by examining *flanker* type across cue condition by subtracting the congruent median response time from the incongruent median response time for each participant. For accuracy data, subtractions were computed using proportion correct.

**Verbal working memory:** Numbers Reversed from the WJ-R (Woodcock & Johnson, 1989) assessed verbal working memory. Participants repeated a sequence of dictated numbers in reverse order. This task consisted of 7 span items, each containing 4 or 5 trials, and ranging from 2–8 numbers in each item. The raw score was converted to a standard score. This measure has good reliability, $r = .87$.

**Visual-spatial working memory:** Spatial Span backward from the Wechsler Intelligence Scale for Children – Fourth Edition Integrated (WISC-IV-Integrated; Wechsler et al., 2004) measured visual-spatial working memory. Participants produced the sequence of tapped blocks in the reverse order of presentation. This task comprised 8 span items, each containing two trials, and ranging from 2–8 tapped blocks. Raw scores were converted to standard scores. Spatial span backward has adequate reliability (internal consistency $\alpha = .81$; test re-test reliability $r = .68$).

**Fine motor skills:** The number of rows completed using both hands on the Purdue Pegboard test measured fine motor skill. For this task, participants pick up and place pins in two rows of holes using both hands simultaneously. Test-retest reliabilities for single trial scores range from $r = .60$ to .76 (Tiffin & Asher, 1948). Scores for both hands were used because children often use both hands for counting and when solving addition or subtraction problems.

## Procedure

Participants were assessed in a single session lasting between 3 and 4 hours depending on the assessment. Most children were assessed at facilities associated with the project but some were assessed in their homes. Children were tested at approximately their 9.5 year mark. Although the ANT and math outcomes were obtained at the 9.5 year mark, fine motor skill and working memory were assessed at the 7.5 and 8.5 year assessment points respectively.

## Statistical Analyses

Group differences on the cognitive measures and math outcomes were examined using ANCOVAs (one way or mixed). All models included SES as a covariate, as well as age at assessment for raw scores. Details of the specific models tested are embedded in the results section below.

To select cognitive variables for mediation models, first-order correlations among the independent variable (IV), dependent variables (DVs), and potential mediators (Ms) were computed. Analyses of mediation effects used a multiple mediation model, directly testing the significance of the indirect effect of the IV on the DV through the potential mediators.

A bootstrapping nonparametric resampling procedure was applied for assessing indirect effects (Preacher & Hayes, 2008), whereby 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. In multiple mediation models, this procedure is used for the estimation of the indirect effect of a mediator while controlling for the other potential mediators included in the model.

This bootstrapping procedure holds statistical power while maintaining reasonable control over the Type I error rate (Preacher & Hayes, 2008), and is thereby superior to other approaches to mediation, such as the product of coefficients approach, the Sobel test, and the commonly used causal steps approach outlined in Baron and Kenny (1986). Bootstrapping is recommended when the assumption of normality of the sampling distribution is questionable, as it may be the case in small samples. Here, the bootstrapping procedure was conducted using the SPSS macro provided by Preacher and Hayes (2008). A point estimate for an indirect effect was considered significant when the bias corrected and accelerated (BCa) confidence interval did not include zero. The BCa confidence intervals account for the often asymmetric point estimate distribution resulting from bootstrapping.

Mediation was used to examine the hypothesis that cognitive variables mediate the effect of group on math outcomes. Models were run only for those math outcomes where performance differed between children with SBM and their typically developing peers (approximate arithmetic, math fluency, and math calculations). Because the mediators and outcomes were assessed at various time points, and there was a mixture of raw and standardized scores, age-residualized scores were computed and entered into the models. When initial models covarying for SES showed no significant effect of SES on outcome, SES was removed from later models.

# Results

## Group Comparisons on Arithmetic Outcomes

One-way ANCOVAs covarying for age at assessment and SES were conducted to examine group differences on the exact and approximate tasks. For the exact arithmetic task, the groups did not significantly differ on accuracy, $F(1,86) = 3.31$, *ns*, or response latency, $F(1,86) = 1.80$, *ns*. For the approximate arithmetic task, the typically developing children outperformed the children with SBM in terms of accuracy, $F(1,83) = 5.38$, $p < .05$, $\eta^2 = .06$, though the groups did not differ in response latency ($F < 1$). Group means for accuracy and response latencies are presented in Table 2 for the exact and approximate arithmetic tasks.

One-way ANCOVAs covarying for SES were run to investigate group differences on the standardized math measures, using standard scores. Typically developing children ($M$ = 108.62, $SD$ = 17.63) outperformed children with SBM ($M$ = 79.21, $SD$ = 24.55) on Math Calculations, $F(1,97) = 29.21$, $p < .001$, $\eta^2 = .23$; and Math Fluency ($M$ = 99.13, $SD$ = 14.37 for typically developing children and $M$ = 85.37, $SD$ = 18.67 for children with SBM), $F(1,95) = 8.69$, $p < .01$, $\eta^2 = .08$.

## Group Comparisons on Cognitive Tasks

**Interactions among group, cue, and flanker on the ANT—**Two Group (SBM versus Typically Developing peers) x 4 Cue (No cue, Center cue, Double cue, and Spatial cue) x 3 Flanker (Congruent, Incongruent, and Neutral) mixed ANCOVAs were performed on accuracy and response time data, covarying for age at assessment and SES, to compare the performance of children with SBM to that of typically developing peers on the ANT. Response time data were positively skewed, so a logarithmic transformation was performed. Mean accuracy and response latencies are presented in Tables 3 and 4 respectively.

For accuracy on the ANT, there was a main effect of cue, $F(3, 261) = 5.72$, $p = .001$, $\eta^2 = .06$, such that both groups of children were less accurate on no cue trials compared to all cued trials, and on spatial cue trials compared to center cue trials. There was also a main effect of flanker, $F(2,174) = 44.04$, $p < .001$, $\eta^2 = .34$, such that both groups were less accurate on incongruent trials compared to congruent and neutral trials, and on neutral trials compared to congruent trials. The interaction between cue and flanker was not significant. The main effect of group was not significant and group did not significantly interact with cue, flanker, or both together.

For correct response latencies, there was a main effect of cue, $F(3,243) = 6.01$, $p = .001$, $\eta^2 = .07$, such that children took longer to respond to no cue trials compared to all cued trials, and within cued trials, spatial cues led to shorter response times than center or double cues. There was also a main effect of flanker, $F(2,162) = 36.76$, $p < 001$, $\eta^2 = .31$, such that response times were slower on incongruent than congruent or neutral trials, and on congruent compared to neutral trials. The group main effect was not significant (p > .05) and there were no significant interactions.

**Cognitive subtractions—**To examine group differences on each attention network, a set of one-way ANCOVAs were carried out with group as the factor, covarying for age at assessment and SES. Means for cognitive subtractions are in Table 5. For accuracy, there was an effect of group for orienting attention, $F(1,84) = 7.88$, $p < .01$, $\eta^2 = .09$, but not for alerting ($F < 1$) or executive attention, $F(1,84) = 1.18$, $p = .28$. In terms of the group effect for orienting attention, children with SBM had a negative score, indicating that they were more accurate on center cue trials than on spatial cue trials, compared to their typically developing peers, who had a positive score, suggesting greater accuracy on spatial cue than center cue trials.

When the subtraction (efficiency) scores for response latency were examined there were no significant effects of group for the alerting, orienting, or executive attention networks (all F's < 1). However, children with SBM may have taken longer to respond to trials with a spatial cue, so spoiled responses (RTs > 1700 msec at which point the trial timed out) were also examined. More children with SBM had at least one spoiled response on spatial cue trials compared to typically developing peers, $\chi^2(1) = 5.94$, $p < .05$.

To investigate group differences on working memory, one-way ANCOVAs, covarying for SES, were conducted using standardized scores from the measures. Children with SBM performed more poorly than their typically developing peers on measures of verbal working memory, $F(1,92) = 6.91$, $p = .01$, $\eta^2 = .07$, and visual-spatial working memory, $F(1,90) = 12.34$, $p = .001$, $\eta^2 = .12$.

A one-way ANCOVA was run to examine group differences on fine motor skills covarying for age at assessment and SES. Children with SBM performed more poorly than typically developing peers, $F(1,83) = 22.88$, $p < .001$, $\eta^2 = .22$. Mean scores for the cognitive tasks are presented in Table 6.

### Mediators of the Effect of Group on Arithmetic Outcomes

Bivariate correlations among the variables are presented in Table 7.

For approximate arithmetic, the total indirect effect for this set of mediators was significant, with a point estimate of −.50 and a 95% BCa CI of −.89 to −.24, indicating that at least one of the variables significantly mediated the effect of group on approximate arithmetic. Group, verbal working memory, visual-spatial working memory, and fine motor skills accounted for a significant proportion of the variance in approximate arithmetic performance, Adjusted $R^2 = .18$, $F(4,72) = 5.25$, $p < .001$. An examination of the indirect effects showed that verbal working memory and fine motor skills were significant mediators, with point estimates of −.16 and −.21 and 95% BCa CIs of −.38 to −.01 and −.50 to −.02. With all mediators entered in the model, the direct effect from group to approximate arithmetic was no longer significant, $b = -.07$, $t = -.26$, $p = .80$ (see Figure 2).

The total indirect effect of group on math fluency through the set of proposed mediators was significant with a point estimate of −10.96 and a 95% BCa CI of −16.91 to −4.52. Group and the proposed set of mediators accounted for a significant proportion of variation in math fluency, Adjusted $R^2 = .31$, $F(4, 83) = 10.63$, $p < .001$. An examination of the specific indirect effects showed that visual-spatial working memory and fine motor skills were significant mediators with point estimates of −3.48 and −5.86 and 95% BCa CIs of −7.49 to

−.23 and −11.39 to −.55. With all mediators entered in the model, the direct effect from group to math fluency was no longer significant, *b* = −2.69, *t* = −.71, *p* = .48 (see Figure 3).

For math calculations, the total indirect effect for this set of mediators was significant with a point estimate of −12.36 and a 95% BCa CI of −19.01 to −6.25. Math calculations were predicted quite well from group, verbal working memory, visual-spatial working memory, and fine motor skills, with Adjusted $R^2$ = .48, $F(4, 83) = 20.89$, $p < .001$. However, only verbal working memory and visual-spatial working memory were found to be significant mediators with point estimates of −3.72 and −4.60 and 95% BCa CIs of −8.10 to −.98 and −9.95 to −.69. With all mediators entered in the model, the direct effect from group to math calculations remained significant, *b* = −11.33, *t* = −2.79, $p < .01$ (see Figure 4).

## Discussion

The present study evaluated both mathematical processing and achievement in children with SBM and their typically developing peers. Moreover, we evaluated attention, working memory, and fine motor skill as mediators of group differences on math outcomes. This study has four unique features: 1) While poor math achievement has been described before, the comparison of exact and approximate arithmetic has not previously been studied in this population; 2) despite a fairly extensive literature using questionnaire-based measures of attention to predict mathematical outcomes in children with math difficulties, direct measures of attention derived from theoretical models have rarely been used to predict mathematical outcomes in children either with or without math difficulties; 3) key cognitive predictors of math have not been considered in a single study using a multiple mediation framework; and 4) this set of cognitive predictors has not been tested in relation to multiple measures of math to determine the specificity of the relation of cognitive abilities to both math processing and achievement.

### Math Skills in SBM

Mathematical processing involves both how mathematical information is processed and age-appropriate achievement in mathematics. Differences between children with SBM and their typically developing peers were found for approximate, but not exact arithmetic. Although the two tasks were identical in terms of item presentation and response requirements, they required that different cognitive processes be brought to bear during problem solving. Success on simple exact arithmetic, particularly addition and multiplication, is thought to rely on having learned math facts through association and repetition, so that math facts may be readily retrieved from semantic memory, and such associative processing has been described as an area of strength in individuals with SBM (Dennis et al., 2006). In contrast, approximate arithmetic may rely to a lesser extent on language-based representations of number and involve accessing and comparing information to abstract representations of quantity. Deficits in this type of processing, which has been referred to as assembled processing (Dennis et al., 2006), is an area of weakness in individuals with SBM.

The findings for exact arithmetic contrast with one previous study (Barnes et al., 2006), which found that children with SBM who had a math disability were less accurate than typically developing peers in generating answers to exact arithmetic problems, and even those children with SBM without a math disability were slower at retrieving addition facts from memory. Differences in findings between the two studies may be due to task differences: While the present study employed a forced-choice task (i.e. selecting the correct answer from two possible choices), Barnes and colleagues used a production task (i.e., producing the correct answer). The findings from the two studies do converge to illustrate that children with SBM are as accurate as typically developing peers on measures of exact arithmetic, though it is unclear whether children with SBM employ more laborious strategies to arrive at the correct answer when the answer, unlike the paradigm used in the current study, is not provided.

Findings generally support previous studies demonstrating children with SBM perform more poorly than typically developing peers on composite measures of computation (e.g., Ayr et al., 2005; Barnes et al., 2006). They performed less well than typically developing peers on a measure of math fact fluency (which differed from the exact arithmetic task in requiring speed and accuracy in generating answers for a sequence of addition, subtraction and multiplication problems) and on a measure requiring single and multi-digit written computation.

### Math-related cognition

Consistent with our predictions and with their neural phenotype (Dennis et al., 2006), children with SBM performed more poorly than typically developing peers on measures of verbal working memory, visual-spatial working memory, and fine motor skill, confirming earlier reports (Dennis & Barnes, 2002; Barnes et al., 2014; Barnes et al, 2011; Hetherington & Dennis, 1999; but see Mammarella et al., 2003).

As predicted from earlier reports and from the neural phenotype, alerting and executive attention were comparable in children with SBM and their typically developing peers, but attention orienting was poorer in the SBM group. Compared to controls, children with SBM had more “timed out” spatial cue trials, consistent with their significant deficits in orienting to exogenous cues (Dennis et al., 2005b). These results are consistent with previous studies of school-age children and infants using a range of attention tasks (Dennis et al., 2005a; 2005b; Taylor et al., 2010). In contrast, adults with dyscalculia are reported to have deficits in alerting and executive attention (Ashkenazi & Henik, 2010).

### The Relation of Cognitive and Mathematical Processing in Children with SBM

Although executive attention was correlated with some math outcomes (see also Blair & Razza, 2007; Geary, 2004; Mazzocco & Kover, 2007), it did not account for group differences in math. Whether the integrity of various attention networks is related to mathematical performance in children with math difficulties with and without neurodevelopmental disorders requires further study; in particular, it would be of interest to determine whether and how the integrity of different attention networks might be related to other aspects of mathematical processing not studied here, such as large number acuity (Mazzocco, Feigenson, & Halberda, 2011) and number line estimation (Geary, Hoard, Nugent, & Byrd-Craven, 2008).

Working memory and fine motor skill were differentially related to arithmetic outcomes: approximate arithmetic, math fluency, and math computations. The relations between math and cognitive skills were complex as discussed below.

Although as expected, visual-spatial working memory was a significant correlate of approximate arithmetic, visual-spatial working memory did not mediate the group difference. Rather, verbal working memory and fine motor skills were both significant mediators. The findings for verbal working memory are consistent with those of Kalaman and LeFevre’s (2007) dual task study showing that verbal working memory was important for solving both exact and approximate double-digit problems. Furthermore, because the cognitive processes brought to bear on a task often depend on characteristics of the task and the strategies used for task completion, the presentation of these problems using symbolic rather than non-symbolic numerical representations and the comparison process involved in selecting the closest *approximate* answer to the single-digit addition problem from two answer choices (e.g., For the problem 2 + 7 is the best answer choice 8 or 6?) might have brought verbal strategies into play.

That fine motor skills mediate the effect of group on approximate arithmetic is of interest. There is evidence that some finger skills may be related to several aspects of number processing, not only those involved in counting and exact arithmetic. Although spatial congruency effects in numerical judgment tasks (the SNARC effect – responses with the right hand are faster for larger numbers and responses with the left hand are faster for smaller numbers) have been linked to a left-right oriented mental number line representation, a representational system based on patterns of finger counting strategies provides an equally good account of these effects (DiLuca, Grana, Semenza, Seron, & Pesenti, 2006). Such findings suggest that fine motor skills might be implicated in many mathematical tasks. That fine motor skills partially account for group differences in approximate arithmetic suggests a broader role for fine motor skills on arithmetic tasks, including those that do not simply involve exact arithmetic. It is worth noting that the fine motor task and the approximate arithmetic task are speeded and require motor responses, which could also partly account for their relation in this study; however, the differences between groups on the approximate arithmetic task were for accuracy rather than response time and the motor demands are minimal.

For math fluency, fine motor skills and visual-spatial working memory mediated group differences. Poor fine motor skills might prevent the use of fingers in early arithmetic problem solving (Barnes et al., 2011) with consequences for later arithmetic performance, including single-digit arithmetic. Similar to what was noted above, the shared speeded component as well as the motor demands of the fine motor and math fluency tasks might also partly account for their relation. Whether slow or imprecise finger counting earlier in development hinders the transition to memory based math fact retrieval in SBM is unclear, although it is known that these children continue to use less developmentally mature counting strategies in single-digit addition problem solving for a longer period of time than typically developing peers (Barnes et al., 2006). Our findings support theories suggesting that fingers and arithmetic are related because of their functional co-development (Butterworth, 1999). Fine motor skills uniquely predicted performance on nonverbal object-based arithmetic (addition and subtraction) in preschoolers with SBM and their typically developing peers even after accounting for several other math-related cognitive abilities and mathematical knowledge from earlier in development (Barnes et al., 2011). Together, these findings suggest that there may be cognitive continuity in nonverbal (non-symbolic) and symbolic arithmetic problem solving from the preschool years, at least through the early to middle elementary grades.

The importance of visual-spatial working memory to math fluency is readily apparent when considering the task and how different single-digit problems are solved. Children in the present study completed predominantly addition and subtraction with limited, if any, exposure to multiplication problems, due to item order. While multiplication is thought to rely on language-based representations of number because it is learned by rote verbal memorization, subtraction and, at times, addition, depending on strategy choice, may involve some form of manipulation of nonverbal quantities (Dehaene et al., 2005; Lee & Kang, 2002; McKenzie, Bull, & Gray, 2003).

On math calculations, both verbal and visual-spatial working memory partially mediated group differences. This finding is not surprising given that working memory is often conceptualized as involving shifting attention, inhibition, monitoring, and retrieval of information from long term memory, all of which are needed for arithmetic performance. Verbal working memory and visual-spatial working memory may differentially contribute to more specific math cognition deficits, depending on which aspects of mathematical skill are being assessed and what strategies children bring to bear to solve math problems (Geary, Hoard, Nugent, & Byrd-Craven, 2007). For example, visual-spatial working memory, possibly related to the use of mental models during problem solving, may be recruited for the completion of new or difficult mathematical skills/concepts whereas verbal working memory may be more often recruited for familiar and/or easy skills/concepts (reviewed in Raghubar et al., 2010). As such, children may have used a mix of strategies and therefore cognitive resources to solve problems ranging from single-digit arithmetic to complex computations and fractions.

## Limitations and Conclusions

The current study did not collect strategy data for arithmetic outcomes, which would have been informative given that evidence suggests different cognitive processes are brought to bear depending on strategy use (Geary et al., 2007), and also given findings with children with SBM suggesting that they use less developmentally mature strategies for longer than typically developing children (Barnes et al., 2006). We employed a numerical-verbal working memory task, shown to be more frequently related to math difficulties than non-numerical measures of working memory (Raghubar et al., 2010). Whether or not similar findings would be obtained using non-numerical measures of verbal working memory remains to be examined. Furthermore, we employed single measures of cognitive constructs, and may have obtained differing results if multiple measures of each construct were administered and combined into a composite measure or latent variable. Additionally, the cognitive measures for working memory and fine motor skills were administered at different time points (1- and 2-years prior, respectively) relative to the math measures, perhaps impacting the strength of the relationships between the two. Finally, our models did not assess the contribution of medical and neurobiological variables, particularly shunt revisions, that are related to some cognitive and academic outcomes and such factors may be important to add to future models predicting academic function in spina bifida (Adzick et al., 2011; Hetherington, Dennis, Barnes, Drake, & Gentili, 2005).

The present study allowed for a more comprehensive investigation of math skills in children with SBM by examining performance in areas of mathematical processing and achievement. A unique component of this study revealed that children with SBM showed strength in exact arithmetic and deficits in approximate arithmetic and other composite measures of math achievement. The use of a direct measure of attention based on theoretical models revealed a specific deficit in attention orienting; these children also showed deficits in working memory and fine motor skills. Examining this set of cognitive processes within a multiple mediation framework served to increase understanding of math and its multidimensional nature. Findings suggested that different cognitive processes may be important for different math outcomes; however, due to the methodological limitations described above, statements about specific relationships cannot be made at this time. It is worth noting that there is currently little evidence for transfer of training of cognitive processes such as working memory and attention on math performance (Ashkenazi & Henik, 2012; see meta-analysis in Melby-Lervåg, & Hulme, 2013). In contrast, research-based skills specific interventions in math may hold some promise for improving mathematical performance in individuals with SBM (Coughlin & Montague, 2011). The effect of combined training in cognitive processes with math-specific interventions is unknown. This type of intervention research may be a fruitful approach to investigate the nature of the relation of cognitive processes to mathematics learning and disability, and provide information pertinent to improving math outcomes in children with and without neurodevelopmental disorders.

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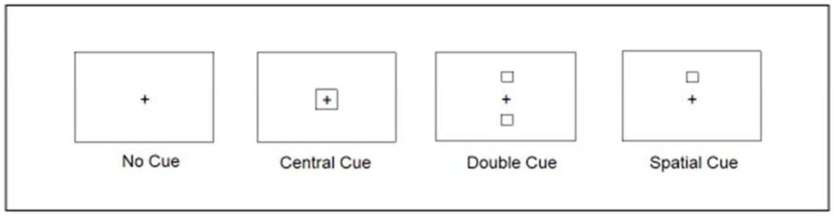


**Figure 1.**

The four warning cue conditions in the Attention Network Test.

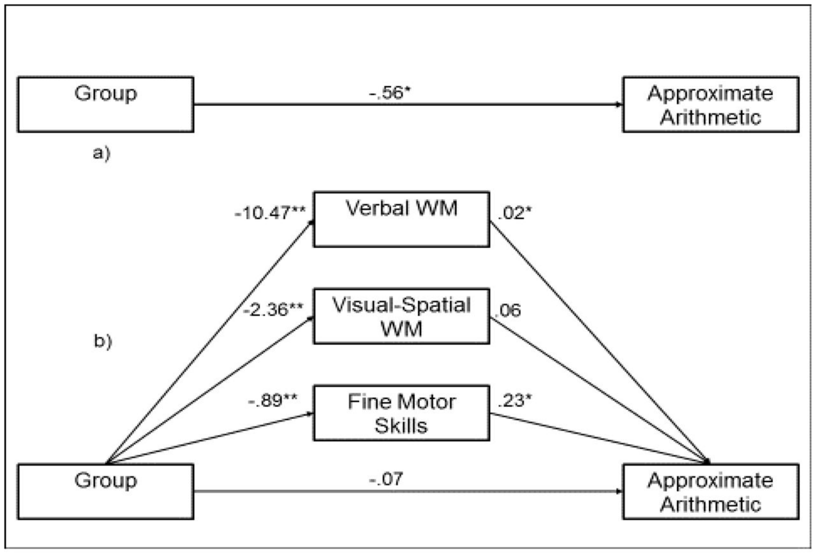


**Figure 2.**

Multiple mediation model of approximate arithmetic: (a) path estimates for the direct effect of group on approximate arithmetic and (b) path estimates for the indirect effects of group on approximate arithmetic. * = $p < .05$; ** = $p < .01$.

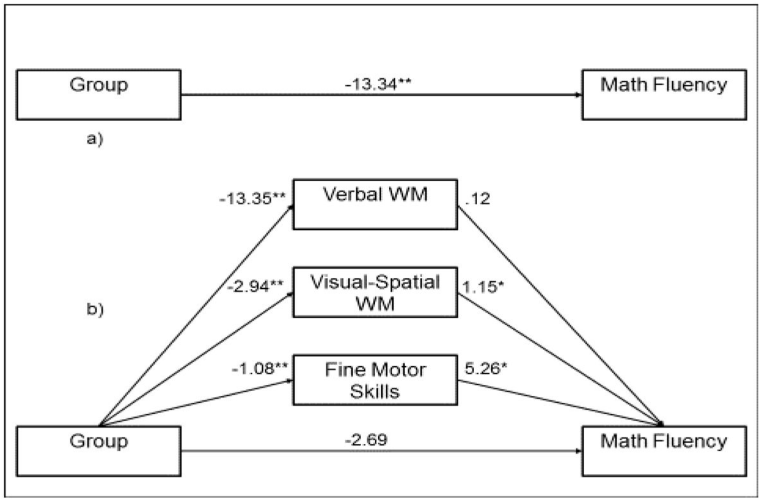


**Figure 3.**
Multiple mediation model of math fluency: (a) path estimates for the direct effect of group on math fluency and (b) path estimates for the indirect effects of group on math fluency. * = $p < .05$; ** = $p < .01$.

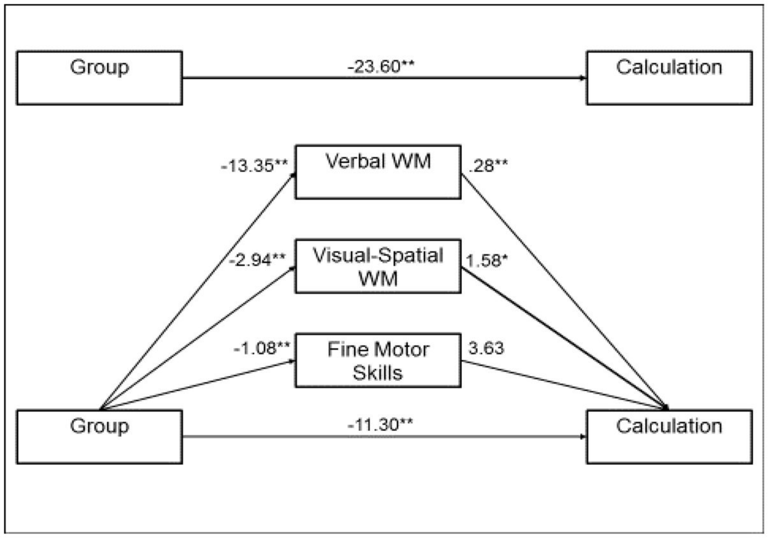


**Figure 4.**
Multiple mediation model of calculation: (a) path estimates for the direct effect of group on calculation and (b) path estimates for the indirect effects of group on calculation. * = $p < .05$; ** = $p < .01$.

## Table 1

Demographic Information for Children with SBM and Their Typically Developing Peers

| Variable | Control | SBM |
|---|---|---|
| Sex (Female)* | 43% | 63% |
| Age (Years) | 9.81 | 9.91 |
| Ethnicity* | | |
| African American | 2% | 10% |
| Caucasian | 62% | 43% |
| Hispanic | 25% | 45% |
| Other | 11% | 2% |
| Hollingshead SES* | 43.72 | 29.29 |
| Nonverbal Skills* | 12.81 | 8.99 |
| Verbal Skills* | 107.55 | 90.39 |

Note.

*Denotes a significant group difference.

Values are scaled or standard scores. Nonverbal skills refer to a composite of Figure Ground and Form Completion subtests from the Leiter International Performance Scale-Revised. Verbal skills refer to the Picture Vocabulary subtest from the Woodcock-Johnson Test of Cognitive Abilities - Revised.

**Table 2**

Mean Accuracy and Response Latencies on Exact and Approximate Arithmetic Tasks

| | **Control** *M* (*SD*) | **SBM** *M* (*SD*) |
|---|---|---|
| **Accuracy (% Correct)** | | |
| Exact Arithmetic | 89.27 (12.71) | 81.31 (18.91) |
| Approximate Arithmetic* | 62.11 (17.38) | 50.35 (25.14) |
| **Response Latencies (ms)** | | |
| Exact Arithmetic | 2723.08 (1006.73) | 3223.84 (1587.48) |
| Approximate Arithmetic | 2293.13 (844.05) | 2535.04 (1278.84) |

*Note.* Standard deviations are presented in parentheses.

**Table 3**

Accuracy by Cue Condition and Flanker Type on the ANT in Children with SBM and Their Typically Developing Peers

| | No Cue<br>***M*** **(*SD*)** | Center<br>***M*** **(*SD*)** | Double<br>***M*** **(*SD*)** | Spatial<br>***M*** **(*SD*)** |
|---|---|---|---|---|
| **SBM** | | | | |
| Congruent | 96.25(7.27) | 97.47(5.21) | 97.82(4.87) | 98.13(6.67) |
| Incongruent | 85.42(19.79) | 89.37(16.28) | 86.28(16.60) | 86.23(18.95) |
| Neutral | 93.77(8.01) | 98.48(4.14) | 97.21(5.33) | 97.47(6.54) |
| **Control** | | | | |
| Congruent | 97.14(6.94) | 97.66(5.56) | 99.48(2.52) | 98.14(5.84) |
| Incongruent | 93.24(10.83) | 91.29(10.73) | 93.15(9.09) | 95.06(8.04) |
| Neutral | 96.09(6.90) | 95.76(7.22) | 96.89(7.51) | 97.42(5.09) |

*Note.* Percent correct is presented with standard deviations in parentheses.

## Table 4

Mean Median RT (ms) by Cue Condition and Flanker Type for the ANT in Children with SBM and Their Typically Developing Peers

| | **No Cue** | **Center** | **Double** | **Spatial** |
|---|---|---|---|---|
| | ***M* (*SD*)** | ***M* (*SD*)** | ***M* (*SD*)** | ***M* (*SD*)** |
| **SBM** | | | | |
| Congruent | 700.17(129.42) | 670.36(137.21) | 659.13(119.14) | 636.60(127.92) |
| Incongruent | 818.83(186.67) | 788.65(191.29) | 824.39(172.68) | 743.86(195.73) |
| Neutral | 666.78(127.87) | 629.03(105.37) | 607.46(109.55) | 582.69(100.89) |
| **Control** | | | | |
| Congruent | 674.14(98.91) | 639.65(98.24) | 632.90(100.21) | 596.29(99.95) |
| Incongruent | 772.32(119.25) | 737.59(108.63) | 740.62(113.47) | 652.45(89.25) |
| Neutral | 670.42(115.96) | 601.59(88.41) | 594.31(90.65) | 573.00(92.07) |

*Note.* Mean median response times are presented with standard deviations in parentheses.

## Table 5

Mean Accuracy and Response Times for Cognitive Subtractions on the ANT

| | **Control** *M* (*SD*) | **SBM** *M* (*SD*) |
|---|---|---|
| **Accuracy** | | |
| Alerting | .0101(.0606) | .0220(.0818) |
| Orienting* | .0187(.0563) | −.0084(.0473) |
| Executive | .0498(.0564) | .1027(.1341) |
| **Response Time (ms)** | | |
| Alerting | 48.69(53.95) | 32.10(59.56) |
| Orienting | 52.49(50.80) | 40.88(74.28) |
| Executive | 90.52(52.31) | 118.00(77.77) |

Note.

*Denotes a significant group difference at $p < .01$;

Standard deviations are presented in parentheses.

## Table 6

Mean Scores on Cognitive Tasks by Group

| | Control<br>*M* (*SD*) | SBM<br>*M* (*SD*) |
|---|---|---|
| Verbal Working Memory* | 111.71 (15.68) | 95.50 (22.82) |
| Visual-Spatial Working Memory* | 11.88 (2.54) | 8.74 (3.75) |
| Fine Motor Skills* | 8.71 (1.77) | 6.58 (2.11) |

*Note.* Standard deviations are presented in parentheses. Standard scores are presented for Verbal Working Memory; Scaled scores are presented for Visual-spatial Working Memory; and raw scores for number of rows are presented for Fine Motor Skills.

*Denotes a group difference.

## Table 7

Bivariate Correlations among Group, Cognitive Predictors, and Math Outcomes

| | Group | Alerting | Orienting | Executive | VWM | VSWM | Fine Motor |
|---|---|---|---|---|---|---|---|
| Group | -- | .10 | −.24* | .21 | −.38** | −.43** | −.53** |
| Approximate Arithmetic | −.27* | .03 | .13 | −.12 | .33** | .32** | .35** |
| Math Fluency | −.39** | −.08 | −.06 | −.37** | .39** | .47** | .51** |
| Math Calculation | −.53** | −.01 | −.05 | −.40** | .52** | .56** | .53** |

*Note.* VWM = Verbal Working Memory; VSWM = Visual-Spatial Working Memory

* = $p < .05$;

** = $p < .01$