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Arithmetic skills and their cognitive correlates in children with acquired and congenital brain disorder

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Abstract

Arithmetic skills and their cognitive correlates were studied in 24 children with myelomeningocele and shunted hydrocephalus (MM), 27 children with severe traumatic brain injuries (TBI), and 26 children with orthopedic injuries (OI). Their average age was 11.56 years ($SD = 2.36$). They completed the WRAT–3 Arithmetic subtest and a subtraction task consisting of 20 problems of varying difficulty, as well as measures of working memory, declarative memory, processing speed, planning skills, and visuospatial abilities. The MM group performed more poorly on the WRAT–3 Arithmetic subtest and the subtraction task than the other two groups, which did not differ from each other on either measure. The groups did not differ in the number of math fact errors or visual-spatial errors on the subtraction task, but the MM group made more procedural errors than the OI group. The five cognitive abilities explained substantial variance in performance on both arithmetic tests; processing speed, working memory, declarative memory, and planning accounted for unique variance. Exploratory analyses showed that the cognitive correlates of arithmetic skills varied across groups and ages. Congenital and acquired brain disorders are associated with distinct patterns of arithmetic skills, which are related to specific cognitive abilities. (*JINS*, 2005, *11*, 249–262.)

Keywords: Arithmetic, Children, Brain disorder

INTRODUCTION

Despite occurring in about 6–7% of children in the United States, mathematical disabilities have received far less attention than reading disabilities (Badian, 1983; Kosc, 1974). Recent advances in neuroscience have greatly expanded our understanding of reading and writing, but less attention has been devoted to mathematics (Garnett & Fleischner, 1987; Ginsburg, 1997). We know relatively little about the typical development of mathematical skills when compared to that of reading and writing, and even less about mathematical disabilities. The overall goal of the current study was to examine mathematical skills and their cognitive correlates in children with congenital and acquired brain disorders.

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Perspectives on Mathematical Disabilities

Three major perspectives have guided the study of mathematical disabilities. Clinical neurologists and neuropsychologists have examined mathematical skills in individuals with focal brain lesions (e.g., Hécaen et al., 1961). Cognitive neuropsychologists have approached the study of mathematical disabilities from an information-processing perspective, focusing on the architecture of cognitive processes in functional terms (e.g., McCloskey et al., 1985). Both the clinical neurology/neuropsychology and cognitive neuropsychology perspectives have focused largely on mathematical disabilities as an acquired disorder in adults. In contrast, research from a developmental perspective has focused on children with specific learning disabilities in mathematics, comparing them to same-aged peers without disabilities (e.g., Geary, 1994).

The three perspectives have converged on a model that classifies mathematical disabilities into three major subtypes: disorders of symbolic representation that reflect difficulties comprehending and producing numbers in either oral or written form; disorders of spatial relationships that entail deficits in the spatial representation of numerical information; and disorders of arithmetic computation that involve deficits in basic math fact retrieval and the execution of arithmetic procedures. Notably, recent research suggests that math fact retrieval and the execution of arithmetic procedures are themselves dissociable processes with distinct neural substrates. Temple (1989, 1991, 1997) has presented case studies of children with mathematical disabilities that demonstrate a double dissociation between math fact retrieval and procedural skills. Additionally, research has shown that fact retrieval deficits are associated with left temporal lobe lesions, whereas procedural deficits are associated with both right- and left-hemisphere lesions (Ashcraft et al., 1992; McCloskey et al., 1991; Spiers, 1987).

Cognitive Substrates of Math Skills

Regardless of subtype, mathematical disabilities are likely to reflect deficits in the specific cognitive abilities that support arithmetic skills (Cirino et al., 2002; Geary, 1994, 2004). Current research implicates at least five distinct cognitive abilities as underlying arithmetic skills: declarative memory, working memory, processing speed, visual-spatial skills, and executive functions.

The development of arithmetic skills depends in part on declarative memory. Children's knowledge of both math facts and arithmetic procedures is eventually stored in semantic memory. Research indicates that children with mathematical disabilities, when compared to nondisabled peers, are less able to rely on semantic memory in the performance of arithmetic. They use direct retrieval of math facts less often, have higher error rates when they do use retrieval, and have very irregular solution times when solving problems (Bull & Johnston, 1997; Geary, 1994; Geary et al., 1991; Geary & Brown, 1992; McLean & Hitch, 1999; Passolunghi & Siegel, 2001). Deficits in semantic memory are likely not restricted only to arithmetic facts; indeed, a more general deficit in declarative memory may underlie some arithmetic disabilities and help to explain the frequent co-occurrence of reading and arithmetic disabilities (Geary, 2004).

Working memory allows children to keep information in mind while performing other mental operations (Geary, 1994; McClean & Hitch, 1999). Working memory is especially critical for performing mathematical problems that have several steps, such as complex addition and subtraction problems involving carrying or borrowing. Children with mathematical disabilities perform more poorly than both age-matched and ability-matched comparison groups on tasks of working memory, such as the WISC–R Digit Span and addition span tasks (Geary et al., 1991; McLean & Hitch, 1999; Passolunghi & Siegel, 2001). However, a previous study did not find differences on a word span task, suggesting that working memory deficits in children with mathematical disabilities may be specifically related to numerical information (Passolunghi & Siegel, 2001).

Processing speed is also related to mathematical skills. One explanation for this relationship is that children with mathematical disabilities are slower at executing all basic numerical processes (Geary, 1993). If children are slow to perform skills such as counting, information in working memory may decay before computations are completed; additionally, mathematical knowledge may be less likely to be transferred to semantic memory. Children with lower mathematical ability are slower on tasks such as visual number matching, cross-out tasks, and other measures of perceptual motor speed (Bull & Johnston, 1997). They also have slower counting rates and solve simple addition problems less quickly (Bull & Johnston, 1997; Geary & Brown, 1992). An alternative explanation for the relationship between processing speed and mathematical skills is that children with mathematical disabilities use a less efficient mix of problem-solving strategies, resulting in differences in overall solution times (Geary, 1993). Children with mathematical disabilities tend to use more immature algorithms that take longer to complete, such as "counting all" *versus* fact retrieval (Geary, 1990, 1993; Geary et al., 1992). When using the same strategy as their nondisabled peers, children with mathematical disabilities do not differ in their average counting speed (Geary, 1990; Geary & Brown, 1992).

Visual-spatial skills also have been implicated in models of mathematical disabilities (Geary, 1993; Hécaen et al., 1961). Rourke and Finlayson (1978) found that children with specific deficits in arithmetic performed significantly worse on tests of visual-perceptual and visual-spatial abilities. Hartje (1987) suggested that the relationship between arithmetic and visual-spatial skills may be moderated by the developmental level of the child. Younger children tend not to have math facts or procedures memorized, so they use objects or their fingers for counting. Thus, visual-spatial abilities may be an important predictor of their mathematical skills. As children get older, and use direct retrieval of math facts and rely on automatic procedures more often, visual-spatial skills may become less important for arithmetic computation (Hartje, 1987).

One other domain of cognitive ability that appears to be related to mathematic skills is executive functioning. Executive functions involve a variety of regulatory and planning skills, such as strategy use, self-monitoring, mental flexibility, sustained attention, and inhibition (Graham & Harris, 1996; Pennington et al., 1996). Geary has suggested that mathematical disabilities may often reflect impairment in a "central executive" that controls attentional and inhibitory processes (Geary, 2004). The early emergence of arithmetic skills in preschool children is related to the development of inhibitory control (Espy et al., 2004), and mathematics disabilities in school-age children may be related to deficiencies in mental flexibility and planning skills (Snow, 1992). Children with poor arithmetic skills have been shown to perform more poorly than children without such deficits on the Wisconsin Card Sorting Task and the Tower of London, two common measures of executive function (Bull & Scerif, 2001; Sikora et al., 2002; Snow, 1992).

Mathematical Skills in Children with Brain Disorders

Most models of mathematical disabilities and associated research have focused either on adults with brain lesions or on children with developmental disorders, and therefore may not be applicable to children with congenital or acquired brain disorders (Rourke & Conway, 1997; Temple, 1997). Yet only recently have neuropsychological and developmental perspectives been combined to study mathematical skills in children with specific brain disorders and neurodevelopmental syndromes, which may provide examples of alternative routes to arithmetic disabilities. For example, children with Turner's syndrome often display specific deficits in mathematics, and recent studies have shown that their computational difficulties reflect a mixture of both procedural errors and poor math fact retrieval (e.g., Rovet et al., 1994; Temple & Marriott, 1998). Survivors of acute lymphoblastic leukemia also display math weaknesses (Kaemingk et al., 2004).

Arithmetic skills have been studied in children with hydrocephalus as well (Barnes et al., 2002). Children with hydrocephalus typically are proficient readers with good word decoding skills, although their reading speed and comprehension may fall below expectations. They also frequently exhibit deficits in math and visual-spatial skills. Barnes et al. (2002) administered a written subtraction task comprised of 20 multicolumn problems (VanLehn, 1982) to children with hydrocephalus resulting from a variety of etiologies, as well as to age-matched and ability-matched healthy controls. Errors on the subtraction problems were coded into three categories: math fact errors, visual-spatial errors, and procedural errors. Procedural errors were further coded as slips if a child made the error only once and bugs if a child made the same error more than once. Children with hydrocephalus did not differ from age-matched peers in the number of problems attempted or in the number of math fact or visual-spatial errors. However, they solved fewer problems correctly and made more procedural errors. Their procedural errors tended to be bugs rather than slips (i.e., errors that occurred more than once). In contrast, children with hydrocephalus did not differ from ability-matched peers in the number of problems attempted or solved correctly. They also made the same number of math fact, visual-spatial, and procedural errors (Barnes et al., 2002) as their ability-matched peers. Thus, the findings suggested a developmental lag in procedural knowledge, rather than a specific disability (Barnes et al., 2002).

The Current Study

The current study involves a replication and extension of the work of Barnes et al. (2002). The study includes children with hydrocephalus, as did Barnes et al. (2002), but is restricted to those with myelomeningocele (MM). MM is the most severe form of spina bifida, a common birth defect resulting from a failure of the spinal cord to close during early embryogenesis. It is commonly associated with brain abnormalities of the posterior fossa, midbrain, and posterior cortex, as well as with hydrocephalus that requires shunting. Children with MM experience significant mathematical difficulties, which persist even into young adulthood (Barnes et al., 2002; Dennis & Barnes, 2002).

The study extends Barnes et al. (2002) by including a second clinical population that has been shown to display mathematical deficits, namely children with traumatic brain injuries (TBI). Children with TBI demonstrate deficits on academic achievement tests, with their lowest scores often occurring in math (Chadwick et al., 1981; Jaffe et al., 1992; Knights et al., 1991; Taylor et al., 2002). However, no research has examined mathematical skills in more detail to determine the specific arithmetic processes that are impaired after TBI. The inclusion of children with TBI also provides an opportunity to determine whether children with distinct brain disorders display unique kinds of mathematical problems.

We administered a standardized measure of mathematical skills, as well as the subtraction task used by Barnes et al. (2002), to children with MM, children with TBI, and a comparison group of healthy peers who had previously sustained orthopedic injuries (OI). All three groups were also administered tests of declarative memory, working memory, processing speed, visuospatial skills, and planning abilities. The first specific aim of the study was to compare the mathematical skills of the three groups. We expected the comparison of the MM and OI groups to yield results similar to those found by Barnes et al. (2002). Specifically, we hypothesized that children with MM would display poorer mathematical skills than the OI group. We also expected them to make more procedural errors on the subtraction task but not to differ in the number of math fact or visual-spatial errors. Children with TBI were also expected to display poorer mathematical skills than the OI group. Moreover, because children with TBI are at risk for deficits in declarative memory, working memory, visual-spatial skills, processing speed, and executive functions (Yeates, 2000), we thought that they would be prone to display both more math fact errors and more procedural errors than the OI group.

The second aim of the study was to examine how various cognitive abilities predict mathematical skills in the three groups. We hypothesized that declarative memory, working memory, processing speed, visual-spatial skills, and planning abilities would collectively and individually predict arithmetic skills. Although all of these cognitive abilities have been shown to be related to mathematical skills when examined individually or in pairs (Bull & Johnston 1997; Bull & Scerif, 2001; Geary, 1990, 1993, 1994; McLean & Hitch, 1999; Rourke & Finlayson, 1978), we are not aware of any previous study that has examined them simultaneously in children. To further explore the relationships

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between cognitive abilities and mathematical skills, we examined whether the relationships varied across the three groups or by age. These exploratory analyses were intended to determine whether certain cognitive abilities are more predictive for certain clinical groups or for younger as compared to older children (Kaemingk et al., 2004).

METHOD

Participants

Participants in the study were recruited as part of a larger study on implicit memory. The study was comprised of three groups: children with MM, all of whom were shunted for hydrocephalus; children who had sustained a severe TBI; and children who had sustained an OI not involving the head. The OI group was chosen for comparison purposes because of its demographic similarities to the two clinical groups. The inclusion of the OI group also serves to control for factors related to the likelihood of accidental injury and the experience of hospitalization as compared to the TBI group.

All children ranged from 8 to 15 years of age at the time of recruitment. The MM group included 24 children recruited from the active patient roster of the Myelomeningocele Clinic at Columbus Children's Hospital. Children were excluded from the MM group if they had any history of neurological complications, brain disease, or brain injury that was not related to spina bifida.

The TBI group included 27 children recruited from the registry of patients maintained by the Trauma Program at Columbus Children's Hospital. Children were included if they had sustained a severe TBI at least 12 months prior to participation. Injuries were considered severe if they resulted in a lowest postresuscitation Glasgow Coma Scale score of 8 or less. Children were excluded if their injury did not fall into the category of closed-head injuries (e.g., injury due to drowning, toxins, projectile wounds, or stroke). Children were also excluded if they had a history of premorbid learning disability, attention deficit disorder, other developmental or neuropsychiatric disorder, or brain disease or injury, based on parent report and a review of medical records. Table 1 presents information regarding years postinjury, lowest postresuscitation Glasgow Coma Scale score, and duration of impaired consciousness (i.e., days unable to follow commands) for the TBI group.

The OI group included 26 children, also recruited from the registry of patients maintained by the Trauma Program at Columbus Children's Hospital. They were included if they had sustained an orthopedic fracture not involving the head that required hospitalization at least 12 months prior to participation. Children were excluded from the OI group if they had a history of learning disability, attention deficit disorder, other developmental or neuropsychiatric disorder, brain disease, or head injury, according to parent report.

In all groups, children were included only if their estimated Verbal Comprehension Index or Perceptual Organization Index was greater than 80, based on a short form of the Wechsler Intelligence Scale for Children–Third Edition (WISC–III; Wechsler, 1991; Donders, 1997). Children in all groups were excluded if they had a history of severe psychiatric disorder resulting in hospitalization, evidence of abuse or neglect, or any sensory or motor impairment that would preclude administration of the study measures. Table 1 summarizes the demographic characteristics of participants. The groups did not differ on any of the demographic variables, including age, gender, race, or socioeconomic status.

Procedure

Participants were scheduled for two separate testing sessions, each lasting approximately 2 hr. During the first session, children completed measures of general intellectual

Table 1. Demographic characteristics of participants by group

	Group					
	MM (*N* = 24)		TBI (*N* = 27)		OI (*N* = 26)	
	%	*n*	%	*n*	%	*n*
Male	54%	13	56%	15	54%	14
Caucasian	92%	22	78%	21	92%	24
	M	*SD*	*M*	*SD*	*M*	*SD*
Hollingshead Four-Factor Index	40.79	11.48	38.88	12.16	42.69	12.87
Age at assessment in years	11.49	2.66	11.73	2.15	11.59	2.33
Years postinjury			2.55	.88	2.41	.35
Lowest postresuscitation GCS score			5.33	1.73		
Duration of impaired consciousness in days			2.81	2.97		

Note. MM = myelomeningocele and shunted hydrocephalus; TBI = traumatic brain injury; OI = orthopedic injury; GCS = Glasgow Coma Scale.

functioning and implicit memory. During the second session, which took place an average of three months after the first ($M = 3.36$ months; range $= 0$ to 16 months), children were administered measures of specific cognitive and academic skills. The measures included tests of arithmetic skills, as well as visual-spatial skills, working memory, processing speed, declarative memory, and planning.

Measures

Arithmetic skills

Arithmetic skills were assessed using two measures. The first was the Arithmetic subtest of the Wide Range Achievement Test–Third Edition (WRAT–3; Wilkinson, 1993), a timed test that yielded age-based standard scores for each participant.

The second measure of arithmetic skill was a subtraction task, consisting of 20 multicolumn subtraction problems of varying difficulty (VanLehn, 1982). Children were asked to complete as many problems as possible, without any time limit, and to show all their work on the subtraction sheet. The task allows a detailed examination of specific error types, including visual-spatial errors, math fact errors, and procedural errors (Barnes et al., 2002). Visual-spatial errors are coded when an incorrect answer results from misalignment of rows or columns, misplacement of digits during borrowing, or overcrowding of written work. Errors are coded as math fact errors when two digits are subtracted incorrectly, regardless of alignment, carrying, or borrowing. Errors are coded as procedural errors if an incorrect algorithm is used. Coding was based on a detailed list of procedural errors developed by VanLehn (1982), such as "smaller from larger," where the child does not borrow but in each column just subtracts the smaller digit from the larger, or "once borrow always borrow," where once the child has borrowed, she continues to borrow in every remaining column of the problem. Procedural errors were also coded as either slips, when a child made the error only once, or bugs, when a child made the same error more than once. Interrater reliability of the error coding was established by comparing independent ratings by the first author and a research assistant on 25% of the protocols from all three groups, and ranged from .91 to .99 for the number of items attempted, number correct, and the numbers of procedural errors, math fact errors, and visual-spatial errors.

Cognitive abilities

General intellectual functioning was assessed using a short form of the Wechsler Intelligence Scale for Children–Third Edition (WISC–III; Wechsler, 1991). The short form provides estimated intelligence quotient (IQ) and index scores that are both reliable and valid (Donders, 1997). The WISC–III Freedom from Distractibility Index was used as a measure of working memory and the Processing Speed Index was used as a measure of processing speed. Visual-spatial skills were assessed using a composite that represented the mean of standard scores from the WISC–III Perceptual Organization Index and the Visual Closure subtest from the Woodcock-Johnson Tests of Cognitive Ability–Revised (WJ–R; Woodcock & Johnson, 1989). Declarative memory skills were assessed using a composite measure drawn from the Children's Memory Scale (CMS; Cohen, 1997), computed as the mean of the Verbal Immediate and Verbal Delayed standard score composites. The latter composites are themselves based on the Stories and Word Pairs subtests, which measure story recall and paired-associates learning, respectively. Planning skills were assessed using the Tower of London (TOL), which was administered according to the procedure outlined by Krikorian et al. (1994). The task involved a total of 10 problems of varying difficulty, with the minimum number of moves to the correct solution for each problem ranging from 2 to 5. Three trials are given for each problem. Three points were awarded for a successful solution on the first trial, two points for a solution on the second trial, and one point for a solution on the third trial. No points were awarded if the problem was not solved after three trials. A total score representing the sum of scores across the 10 problems was used to represent planning ability in the current study.

Data Analysis

The first set of analyses involved an examination of group differences in general intellectual functioning and academic skills. One-way analyses of variance (ANOVA) were used to assess group differences in WISC–III Full Scale IQ, as well as the Verbal Comprehension, Perceptual Organization, Freedom from Distractibility, and Processing Speed indexes. One-way ANOVA was also used to assess group differences on the WRAT–3 Reading and Arithmetic subtests, using standard scores as the dependent variables. One-way analyses of covariance (ANCOVA) were used to assess group differences on the subtraction task, using age as a covariate. Dependent variables included the number of items attempted, the number of correct answers, and the numbers of procedural errors, math fact errors, and visual-spatial errors. Planned contrasts were conducted to compare the MM and OI groups and the TBI and OI groups. Effect sizes were assessed using eta^2 for overall group differences and Cohen's d for planned contrasts. To assess the validity of the measures derived from the subtraction task, regression analyses were conducted to determine whether the number of correct answers and number of procedural and math fact errors accounted for significant variance in the WRAT–3 Arithmetic subtest across groups.

The second set of analyses focused on the cognitive correlates of arithmetic skills. Regression analyses were conducted to determine whether the five measures of cognitive ability accounted for significant variance, collectively and individually, on the WRAT–3 Arithmetic subtest and the subtraction task. Dummy variables were entered first in the analyses to control for group membership, along with age.

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In the second step, five cognitive variables were entered as predictors of arithmetic performance: declarative memory (CMS composite), working memory (WISC–III Freedom from Distractibility Index), processing speed (WISC–III Processing Speed Index), visual-spatial skills (WJ–R Visual Closure and WISC–III Perceptual Organization Index composite), and planning skills (TOL total score).

Additional exploratory analyses were also conducted to determine if the relationship between cognitive abilities and arithmetic skills varied by age or group membership. To examine whether age moderated the relationship between cognitive abilities and arithmetic skill, interaction terms were created by multiplying age by each cognitive measure. The five interaction terms were then entered together as a third step in the regression analysis (i.e., after age, group membership, and the five cognitive measures). To examine whether group membership was a moderator, interaction terms were created by multiplying the dummy variables for group membership with each measure of cognitive ability. Differential prediction across groups was assessed by conducting five separate regression analyses testing the total contribution of the two interaction terms associated with each cognitive measure, over and above the collective contributions of group membership, age, and the five cognitive abilities.

RESULTS

Between-Group Comparisons of Cognitive and Arithmetic Skills

The groups differed significantly on the WISC–III Full Scale IQ, $F(2,74) = 7.48$, $p < .001$, $eta^2 = .17$, and the Perceptual Organization and Processing Speed index scores, $F(2,74) = 6.48$, $p < .001$, $eta^2 = .16$, and $F(2,74) = 9.29$, $p < .001$, $eta^2 = .20$, respectively (see Table 2). Group differences on the Verbal Comprehension and Freedom from Distractibility index scores approached significance (both $p < .07$, both $eta^2 > .07$). *Post hoc* comparisons using Bonferroni-corrected *t* tests revealed that the MM group was significantly lower than the OI group on Full Scale IQ ($d = 1.00$) and the Perceptual Organization and Processing Speed Indexes ($d = .92$ and 1.03, respectively), while the TBI and OI group differed only on the Perceptual Organization Index ($d = .66$). The MM and TBI groups differed significantly on the Processing Speed Index, with the MM group performing more poorly than the TBI group ($d = .87$). The groups also differed significantly on the WRAT–3 Arithmetic subtest, $F(2,74) = 7.03$, $p < .01$, $eta^2 = .16$, but not on the Reading subtest, $F(2,74) = .26$, $p > .05$, $eta^2 = .01$. *Post hoc* tests revealed that the MM group performed more poorly on the Arithmetic subtest than the TBI and OI groups ($d = .69$ and .96, respectively) but the latter two groups did not differ significantly ($d = .27$).

On the subtraction task, the groups differed significantly in both the number of problems attempted, $F(2,73) = 6.36$, $p < .01$, $eta^2 = .14$, and the number correct, $F(2,73) = 7.23$, $p < .001$, $eta^2 = .16$ (see Table 3). Planned contrasts showed that the MM group attempted fewer problems and made fewer correct answers than the OI group ($d = .80$ and .90, respectively). The TBI and OI groups did not differ in the number of problems attempted or the number of correct answers ($d = .01$ and .28, respectively).

Prior to comparing the groups for different types of errors, we examined the number of problems attempted in all groups. The majority of children attempted at least 18 or more of the 20 problems, but 11 children, mostly from the MM group, attempted very few or none of the problems. To control for differences in the number of problems attempted, the analyses of specific error types were restricted to children who had attempted at least 18 of the subtraction problems. This included 16 children in the MM group, 26 in the TBI group, and 24 in the OI group. Omnibus group comparisons did not detect significant group differences for pro-

Table 2. WISC–III and WRAT standard scores by group

	Group					
	MM		TBI		OI	
WISC–III score	*M*	*SD*	*M*	*SD*	*M*	*SD*
Full Scale IQ*	89.33[a]	13.36	95.85[b]	13.49	104.42[b]	14.66
Verbal Comprehension Index	96.00	15.69	98.81	14.12	106.04	16.00
Perceptual Organization Index*	90.86[a]	15.38	95.15[a]	14.76	106.31[b]	17.07
Freedom from Distractibility Index	94.08	15.82	99.48	13.27	103.96	13.13
Processing Speed Index*	86.46[a]	14.08	99.48[b]	13.27	103.15[b]	11.67
WRAT–3 score						
Reading	100.08	22.66	99.00	15.85	102.38	13.19
Arithmetic*	86.33[a]	17.20	97.81[b]	16.98	102.27[b]	11.52

Note. MM = myelomeningocele and shunted hydrocephalus; TBI = traumatic brain injury; OI = orthopedic injury; WISC–III = Wechsler Intelligence Scale for Children–Third Edition; WRAT–3 = Wide Range Achievement Test–Third Edition; groups with different superscripts differ significantly on *post hoc* comparisons, $p < .05$.
*Overall group comparison significant, $p < .05$.

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Table 3. Performance on the subtraction task by group

	Group					
	MM		TBI		OI	
	M	*SD*	*M*	*SD*	*M*	*SD*
N	24		27		26	
Number attempted*,#	14.33	8.57	19.26	3.85	19.19	3.56
Number correct*,#	9.04	7.40	13.37	6.34	15.31	5.86
N	16		26		24	
Procedural errors#	7.19	5.95	6.69	7.11	4.00	6.24
Slips	2.06	1.88	1.54	1.36	1.17	1.24
Bugs*,#	1.31	1.08	1.04	1.18	.54	.83
Math fact errors	.81	1.22	.62	1.10	.58	1.06
Visual-spatial errors	.56	1.75	.04	.20	.13	.45

Note. MM = myelomeningocele and shunted hydrocephalus; TBI = traumatic brain injury; OI = orthopedic injury.
*Overall group comparison significant, $p < .05$.
#Planned contrast of MM and OI group significant, $p < .05$.

cedural errors, math fact errors, or visual-spatial errors, all $eta^2 < .04$ (see Table 3). However, in planned contrasts, the MM group made significantly more procedural errors than the OI group ($p < .05$, $d = .48$). The MM and OI groups did not differ in the number of math fact errors or visual-spatial errors. None of the planned contrasts involving the TBI and OI groups were significant.

Each child's procedural errors were further coded as either slips or bugs, depending on whether the child made the same error more than once. The groups did not differ overall in the number of slips, but did differ significantly in the number of bugs, $F(2,62) = 3.54$, $p < .05$, $eta^2 = .10$ (see Table 3). In planned contrasts, neither the MM group nor the TBI group differed significantly in the number of slips as compared to the OI group, although the difference between the MM and OI groups approached significance ($p < .07$, $d = .60$). The MM group made significantly more bugs than the OI group ($p < .05$, $d = .72$), while the difference between the TBI and OI groups approached significance ($p < .10$, $d = .47$).

The children's procedural errors were also examined qualitatively to determine whether the groups differed in the types of errors they made. Across all groups, four procedural errors were the most common bugs. The first was *smaller from larger*, in which the child does not borrow but subtracts the smaller digit from the larger one in each column. The second most common bug was *N = N except after borrow*, in which the child thinks $0–N = N$ except when the column has been borrowed from. The third error was *borrow no decrement*, in which the child adds 10 correctly when borrowing but doesn't change any columns to the left. The fourth was *borrow across zero*, in which the child, when borrowing across a zero, skips over the zero to borrow from the next column. Similar numbers of children in all three groups made these procedural errors as bugs, but the children with MM—and to a lesser extent the children with TBI—made those errors more repetitively than the children in the OI group. In other words, the children with brain disorders made errors that were qualitatively similar to those of typically developing children, but they made the errors more persistently.

Performance on the subtraction task was a significant predictor of the WRAT–3 Arithmetic standard score. Age and the two dummy variables for group membership accounted for 17% of the variance in WRAT–3 Arithmetic subtest performance, $F(3,73) = 4.85$, $p < .01$. When the number correct on the subtraction task was entered in the second step of the regression, it accounted for an additional 40% of the variance, $F(1,72) = 65.32$, $p < .001$. The second regression analysis, which examined whether the number of procedural and math fact errors accounted for significant variance in the WRAT–3 Arithmetic subtest, was restricted to children who had attempted at least 18 of the subtraction problems. When math fact errors and procedural errors were entered in the second step of the regression, they accounted for 29% of the total variance, $F(2,60) = 14.14$, $p < .001$. The number of procedural errors accounted for a significant amount of unique variance, $t = -4.63$, $p < .001$, and the number of math fact errors approached significance, $t = -1.87$, $p < .07$.

Cognitive Correlates of Arithmetic Skills

Pooled within-group correlations between the five measures of cognitive abilities, as well as between these measures and arithmetic performance, can be seen in Table 4. The Table shows correlations ranging from small to large based on conventional definitions of effect size.

Collectively, the five cognitive variables accounted for significant variance in arithmetic skills, explaining an additional 47% of the variance in the WRAT–3 Arithmetic standard score, $F(5,66) = 17.70$, $p < .001$, and 27% of the variance in the number correct on the subtraction task, $F(5,66) = 9.21$, $p < .001$ (see Table 5). The cognitive abil-

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Table 4. Pooled within-group correlations

	Declarative memory	Working memory	Processing speed	Visual-Spatial skills	Planning skills	WRAT–3 Arithmetic
Working memory	.42					
Processing speed	.18	.31				
Visual-spatial skills	.20	.23	.33			
Planning	.16	.13	.02	.09		
WRAT–3 Arithmetic	.46	.61	.56	.34	.14	
Subtraction Task number correct	.48	.41	.28	.22	.41	.63

ities that accounted for significant unique variance in the WRAT–3 Arithmetic standard score were working memory, $t = 4.08$, $p < .001$, processing speed, $t = 4.22$, $p < .001$, and declarative memory, $t = 2.40$, $p < .05$. Declarative memory, $t = 3.58$, $p < .001$, and planning skills, $t = 2.09$, $p < .05$, both accounted for unique variance on the subtraction task; processing speed approached significance as a predictor, $t = 1.90$, $p < .06$.

Interaction terms were examined to determine if the relationship between cognitive abilities and arithmetic skills varied across age. Collectively, the five interaction terms accounted for 8% of the variance in the WRAT–3 Arithmetic standard score, $F(5,61) = 3.66$, $p < .01$ (see Table 5). The interactions involving processing speed, $t = -3.55$, $p < .001$, declarative memory, $t = -2.26$, $p < .05$, and visual-spatial skills, $t = 3.37$, $p < .001$, accounted for unique variance. The five interaction terms did not account collectively for significant variance in the subtraction task, $F(5,61) = 2.09$, $p > .05$. However, the interactions involving processing speed, $t = -2.86$, $p < .01$, and visual-spatial skills, $t = 2.04$, $p < .05$, accounted for unique variance.

Table 5. Regression analysis with cognitive abilities as predictors of arithmetic skills

	WRAT–3 Arithmetic Standard Score	Subtraction Task Number Correct
Step 1 β		
MM *vs.* OI	−.47**	−.45**
TBI *vs.* OI	−.16	−.19
Age at testing	.07	.43**
Total R^2 for Step 1	.18*	.35**
Step 2 β		
Working memory	.36**	.16
Processing speed	.38**	.18
Planning	.02	.18*
Declarative memory	.21*	.33**
Visual spatial skills	.09	.04
ΔR^2 for Step 2	.47**	.27**
Step 3 β		
Age × working memory	.22	.48
Age × processing speed	−2.11**	−1.83*
Age × planning	.10	−.26
Age × declarative memory	−1.35*	−.83
Age × visual-spatial skills	2.63**	1.75*
ΔR^2 for Step 3	.08*	.05

Note. Interaction terms were constructed by multiplying age by each specific cognitive measure. The five interaction terms were tested simultaneously. The differences in Step 1 for the WRAT–3 compared to Table 5 are due to different sample sizes; two children did not complete all measures of cognitive abilities. WRAT–3 = Wide Range Achievement Test–Third Edition; MM = myelomeningocele and shunted hydrocephalus; TBI = traumatic brain injury; OI = orthopedic injury.
*$p < .05$, **$p < .001$.

The significant interactions were interpreted by dividing the sample into younger and older age groups at the median age (Aiken & West, 1991). Regression analyses were conducted within the two age groups separately, and the linear relationship between each cognitive ability and arithmetic skill was graphed for each age group. The results indicated that processing speed and declarative memory were stronger predictors of arithmetic skills for younger children than for older children in this sample, while visual-spatial skill was a stronger predictor for the older children than for younger children.

Interaction terms also were examined to determine if the relationship between cognitive abilities and arithmetic skills varied across groups. We conducted five separate regression analyses, testing the total contribution of the two interaction terms associated with each cognitive ability over and above the collective contributions of group membership, age, and the five cognitive abilities. When the WRAT–3 Arithmetic standard score was used as the dependent variable, the only significant interaction involved the Tower of London, R^2 change = .05, $F(2,64) = 5.02$, $p < .01$ (see Table 6). The standardized Beta coefficient for the interaction term was significant for the MM group ($p < .05$) but the interaction term for the TBI group was not ($p > .05$). This suggests that planning was a stronger predictor of performance on the WRAT–3 for the MM group than for the OI group, but that planning did not differ in importance as a predictor in the TBI and OI groups.

When performance on the subtraction task was used as the dependent variable, the only significant interaction involved the visual-spatial composite, R^2 change = .04, $F(2,64) = 4.69$, $p < .05$. The standardized regression coefficient for the TBI group was significant ($p < .05$) but the

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Table 6. Summary of group by cognitive ability interactions as predictors of arithmetic skills

	Cognitive ability				
Dependent variable	Working memory	Processing speed	Planning	Declarative memory	Visual-spatial skills
WRAT–3 Standard Score					
MM *vs.* OI β	1.10	−.03	2.30*	.40	.49
TBI *vs.* OI β	.59	.51	1.30	.70	1.31
ΔR^2 for both interaction terms	.02	.01	.04*	.01	.02
Subtraction Task Number Correct					
MM *vs.* OI β	−.30	−.73	.86	.04	−.43
TBI *vs.* OI β	−.69	−.58	.21	.13	1.47*
ΔR^2 for both interaction terms	.01	.01	.01	.00	.04*

Note. Group membership was represented by two dummy variables. Interaction terms were constructed by multiplying each dummy variable by each specific cognitive measure. Each set of interaction terms was tested in separate analyses, after controlling for group membership, age, and the five cognitive measures. WRAT–3 = Wide Range Achievement Test–Third Edition; MM = myelomeningocele and shunted hydrocephalus; TBI = traumatic brain injury; OI = orthopedic injury.
*$p < .05$.

interaction term for the MM group was not ($p > .05$). Thus, visual-spatial skill was a stronger predictor of performance on the subtraction task in the TBI group than in the OI group, but visual-spatial skill was of equivalent importance in the MM and OI groups.

DISCUSSION

Group Differences in Arithmetic Skills

The first aim of the current study was to compare the arithmetic skills of children with MM or TBI to those of healthy peers. As expected, the MM group displayed poorer arithmetic skills than the OI group. They scored lower on the WRAT–3 Arithmetic subtest, and attempted significantly fewer problems and gave more incorrect answers on the subtraction task than the OI group. The MM group also made more procedural errors and repeated those errors more often than the OI group, although the errors did not differ in kind from those made by the OI group. These results are consistent with previous research showing that children with MM display difficulties with mathematics that reflect a lag in the development of procedural skills. A recent study (Dennis & Barnes, 2002) demonstrated that these difficulties continue into young adulthood, and therefore have serious implications for daily living, as math is used in many common situations such as buying groceries, paying bills, and balancing a checkbook.

Children with TBI were also expected to display poorer arithmetic skills than healthy peers. Although research has not focused on specific mathematical disabilities in TBI, children with severe TBI have shown significantly lower academic achievement than children without TBI, especially in math (Chadwick et al., 1981; Ewing-Cobbs et al., 1998; Taylor et al., 2002). However, in the current study, children with TBI did not display arithmetic deficits. The TBI group did not differ significantly from the OI group on the WRAT–3 Arithmetic subtest or in the number of attempted problems or correct answers on the subtraction task. They also did not differ from the OI group in types of errors on the subtraction task, although they showed a trend toward more procedural bugs. Thus, computational arithmetic deficits in children with TBI may be less pronounced and more subtle than those in children with MM. This may be particularly true when a substantial amount of time has passed since the injury; the current sample was seen on average more than 2 years postinjury. Our results may differ from those of previous studies of childhood TBI because of differences in the mathematical skills assessed; previous studies have used measures that tap complex mathematical abilities, in addition to the computational skills emphasized by the measures in the current study (Chadwick et al., 1981; Ewing-Cobbs et al., 1998; Taylor et al., 2002). Another reason for the difference in findings may be limited power. The sample size of the three groups in the current study was modest, making it difficult to detect small to medium effects in the group comparisons. Significant differences may have been detected between the TBI and OI groups with larger sample sizes and greater power.

Notably, children in all three groups made relatively few math fact errors on the subtraction task. Thus, children who attempted the subtraction problems apparently were able to use basic math facts, regardless of the strategy they relied on to do so. The children in all three groups also made relatively few visual-spatial errors, suggesting that misalignment of columns and other visuospatial difficulties are not a significant problem for children in either clinical group. These results are consistent with those found by Barnes et al. (2002).

The results also confirm that the subtraction task provides a valid measure of arithmetic skills. The number of correct answers on the subtraction task accounted for 40% of the variance in performance on the WRAT–3 Arithmetic subtest. In addition, the number of procedural errors and

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math fact errors accounted for 29% of the total variance in the WRAT–3. These are both large effect sizes. The subtraction task assesses basic computational skills that provide the foundation for all higher-order mathematics. If a child performs poorly on subtraction problems, they have not mastered basic computation and are not likely to be able to solve more complex mathematical problems. Thus, if a child performs poorly on the subtraction task, they will most likely perform poorly on the WRAT–3, which assesses basic calculation skills as well as higher-order mathematics (e.g., fractions, decimals, algebra).

Cognitive Correlates of Arithmetic Skills

The second aim of the study was to examine how various cognitive abilities predict mathematical skills within the three groups of participants. After controlling for group membership and age, the five cognitive abilities accounted for a large amount of the variance in performance on both the WRAT–3 and the subtraction task. Working memory, processing speed, and declarative memory each accounted for unique variance on the WRAT–3, while planning and declarative memory accounted for unique variance on the subtraction task.

Working memory is the limited capacity system responsible for maintaining and transforming information held in mind temporarily (Baddeley & Hitch, 1994). In mathematics, this system allows children to maintain math facts in mind while performing the multiple steps involved in more complex problems. Geary (1993, 2004) suggested that children with mathematical disabilities have poor working memory. His research, as well as that of McLean and Hitch (1999), showed that children with mathematical disabilities perform more poorly on tests of working memory. Passolunghi and Siegel (2001) suggested that the working memory deficit is specifically related to numerical information, because the children with mathematical disabilities in their study performed poorly on digit span but not on a word span task. In the current study, working memory was assessed through digit span and oral arithmetic subtests. Thus, the association between working memory and arithmetic skills may reflect the specific numerical nature of the measures used in this study. Notably, working memory accounted for unique variance only on the WRAT–3 Arithmetic subtest and not on the subtraction task. The WRAT–3 Arithmetic subtest includes more multiple-digit problems than the subtraction task; it also includes higher-order mathematics problems (e.g., fractions, decimals, algebra) that involve a number of intermediate steps to completion. The difference between tasks may account for the relatively stronger relationship between working memory and arithmetic skill on the WRAT–3 as opposed to the subtraction task.

Processing speed also was found to account for unique variance in arithmetic skills. Processing speed works in conjunction with working memory to allow a child to perform math problems; the abilities are correlated, but make independent contributions to the prediction of arithmetic skills. Processing speed is reflected in the amount of time needed to complete a given math problem, including the time working memory is used to hold math facts in mind and perform intermediate steps such as carrying and borrowing. Geary (1994) suggested that processing speed is an important aspect of arithmetic because slowing increases the risk that a child will lose pieces of information needed to finish the arithmetic problem correctly. Bull and Johnston (1997) found that children with low mathematical ability were significantly slower than children with high mathematical ability on tests of processing speed. However, some research suggests that the relationship between processing speed and arithmetic reflects the strategies children use to perform math problems, not their overall processing speed (Geary & Brown, 1992). The current study did not measure counting speed or strategy use, and instead relied on general, nonnumerical measures of processing speed. Thus, the relationship between processing speed and arithmetic found in this study suggests a more general association between processing speed and mathematical skills, rather than one mediated solely by the use of different strategies. Notably, processing speed accounted for unique variance only on the WRAT–3 Arithmetic subtest and not on the subtraction task. The WRAT–3 Arithmetic subtest is timed, so that performance depends in part on speed of performance. In contrast, the subtraction task was not timed. This difference in task demands may help to explain the relatively stronger relationship between processing speed and arithmetic skill on the WRAT–3 as opposed to the subtraction task.

Declarative memory was found to explain unique variance in performance on both the WRAT–3 and the subtraction task. Knowledge of both math facts and arithmetic procedures are dependent on declarative memory. Research examining the relationship between declarative memory and arithmetic has focused on strategy use. Researchers have hypothesized that children who use direct retrieval of math facts have these facts, as well as arithmetic procedures, stored in semantic memory. Geary and Brown (1992) found that gifted children used direct retrieval more often than average or math-disabled children, and that average children used direct retrieval more often than the math-disabled children. Across all groups, the frequency of retrieving correct answers was significantly correlated with performance on a standardized math test. Based on these results, Geary and Brown (1992) concluded that semantic memory of basic math facts is the factor underlying the observed group differences in arithmetic. Subsequently, Geary et al. (1992) showed that children with mathematical disabilities have an immature understanding of counting procedures, which are also assumed to be stored in semantic memory. Unlike the studies cited above, the current study did not assess strategy use or counting knowledge. Instead, declarative memory was measured using measures of story recall and paired-associates learning. Thus, the results of the current study support previous hypotheses of a general relationship between declarative memory and arithmetic skill that is not restricted to semantic memory for numerical information (Geary, 2004).

Planning skills also were found to be related to arithmetic skills. These results are consistent with previous research that has demonstrated a relationship between executive functions and performance on standardized tests of arithmetic (Bull et al., 1999; Bull & Scerif, 2001). The current results, which involve the Tower of London, complement those of Sikora et al. (2002), who found that children with arithmetic learning disabilities performed more poorly on the Tower of London than children with reading disabilities or children without learning disabilities. They also are congruent with research showing that children with TBI often display deficits in planning skills on the Tower of London (Levin et al., 1996). In the current study, planning abilities as assessed by the Tower of London accounted for unique variance in the subtraction task but not in the WRAT–3. The reason for this discrepancy is not clear, because both arithmetic tasks would appear to require planning skills; moreover, as discussed in the subsequent section, planning ability did predict performance on the WRAT–3 for children in the MM group. Across groups, though, the results suggest that the WRAT–3 is more dependent on working memory, declarative memory, and processing speed, and less dependent on planning abilities, as compared to the subtraction task.

Developmental and Group Variation in Cognitive Correlates

The study also examined whether the relationships between cognitive abilities and mathematical skills were consistent across groups and age. The goal of these exploratory analyses was to determine whether certain cognitive abilities are uniquely important for the two clinical groups and whether their importance varies developmentally. Planning skills as measured by the Tower of London accounted for unique variance in WRAT–3 performance only in the MM group, and not in the TBI or OI groups. The reason that no relationship was obtained in the TBI and OI groups is unclear, particularly since planning skills did predict arithmetic skills on the subtraction task in those groups. Despite the group differences in prediction on the WRAT–3, therefore, planning skills may not hold unique importance as a predictor of arithmetic skills for certain childhood brain disorders.

The relationship between visual-spatial skills and arithmetic also varied significantly across groups. Visual-spatial skill was a significant predictor of performance on the subtraction task for the TBI group but not for the MM or OI groups. The reason for this group difference also is unclear, as past research has shown that children with MM as well as children with TBI exhibit deficits in visual-spatial skills (Brookshire et al., 1995; Levin & Eisenberg, 1979). The isolated finding could be spurious; on the other hand, it may suggest that visual-spatial skills are important for the complex types of math that may be especially troublesome for children with TBI.

Evidence also was found of developmental variations in the relationship between cognitive abilities and arithmetic skill. Three cognitive abilities were found to vary in importance as predictors according to age: processing speed, declarative memory, and visual-spatial skills. The significant interaction between age and processing speed occurred because the relationship between arithmetic performance and processing speed was stronger for younger than for older children. The literature suggests that younger children rely on strategies that require more time, such as counting on their fingers or in their head, rather than retrieving math facts directly from memory (Geary, 1994). In contrast, older children are able to directly retrieve math facts and calculation procedures from memory, so that processing speed may play less of a role for them on measures of computational skill. A similar explanation may hold for the interaction between age and declarative memory, which also was more strongly related to arithmetic skills for younger than for older children. The relationship to declarative memory may be stronger for younger children because they are still forming the associations needed to support retrieval of math facts and calculation rules (Geary, 2004). On the other hand, for older children, the relationship may be weaker because they already have stored the information needed to perform arithmetic problems in semantic memory and are able to consistently retrieve this information.

Unlike processing speed and declarative memory, visual-spatial skills were more strongly related to performance for older children. Although visual-spatial deficits were a component of Hécaen et al.'s (1961) original model of acalculia and Geary's model of mathematical disabilities (1994, 2004), research has not always found a relationship between mathematical and visual-spatial skills. The current findings suggest that visual-spatial skills may be less important for younger children, who are mastering simple addition and subtraction, often in single columns. In contrast, older children must complete problems that include multiple digits, as well as fractions, decimals, and algebraic equations. Visual-spatial skills are likely to play a bigger role in completing these sorts of problems. These results may appear to contradict Hartje's (1987) assertion that visual-spatial skills are more important for younger children, who use objects or their fingers for counting, than for older children, who use direct retrieval more often (Hartje, 1987). However, the young children in Hartje's studies were preschoolers, just learning to count, while the young children in this study were school-aged, and beginning to master addition and subtraction. In contrast, the older children in the current study were in middle school, and would be expected to be able to complete multicolumn problems, as well as higher-order arithmetic, such as algebra, that places more of an emphasis on spatial skills. Thus, the role of visual-spatial skills as a predictor of mathematics may fluctuate during the course of development.

Study Limitations

The current study is not without limitations. One was the use of the WISC–III Freedom from Distractibility Index as the measure of working memory. The Freedom from Distractibility Index includes the Arithmetic subtest, which appraises oral arithmetic skills, and may therefore confound the assessment of working memory with that of mathematical ability. However, the results of the study were essentially unchanged when the analyses were repeated using only the standard score from the Digit Span subtest as the measure of working memory. Of course, the Digit Span subtest can itself be criticized, both for combining forward and backward span (Reynolds, 1997) and for failing to differentiate the theoretical components of working memory, such as the central executive and the phonological loop (Baddeley & Hitch, 1994). On the other hand, the Freedom from Distractibility Index has demonstrated satisfactory reliability and validity as a measure of working memory in previous research (Riccio et al., 1997). Although future research should delineate which components of working memory are most strongly related to arithmetic skills, the current findings confirm that working memory is an important correlate of arithmetic skills in children.

The study was also limited by the use of a single measure of executive functions (other than working memory), namely the Tower of London. The construct of executive functions cannot be completely captured by a single measure, and factor analytic studies of measures of executive function confirm that they do not load on a single dimension (Graham & Harris, 1996; Pennington, 1997; Pennington et al., 1996). Future research on the relationship of executive functions to arithmetic skills should incorporate multiple measures based on specific theories of executive function, to help tease apart the contributions of dimensions such as inhibitory control, working memory, and planning (Espy et al., 2004).

The study could also be criticized for not matching children individually for reading ability or eliminating children with poor reading skills (cf. Barnes et al., 2002). However, we eliminated children from the OI and TBI groups who reportedly had premorbid learning disabilities, and the three groups did not differ in their average performance on the WRAT–3 reading subtest and all had mean scores in the average range. Additionally, only six children out of the total sample of 77 had WRAT–3 reading scores below the 10th percentile (i.e., standard score < 80), and the MM, TBI, and OI groups did not differ significantly in the proportion of children with low scores. Thus, reading ability is not likely to present a major confound in the current study.

Implications and Future Research Directions

The current study illustrates the benefit of combining neuropsychological and developmental perspectives in the study of arithmetic skills through the study of children with acquired and congenital brain disorders. The study's findings not only shed light on the effects of childhood brain disorder, but also contribute to our understanding of the normal development of arithmetic skills. Additionally, the findings may hold important practical implications. For many children with MM, unfortunately, arithmetic disabilities are a significant and life-long problem (Barnes et al., 2002). The current results indicate that children with MM make procedural errors that do not differ in kind from healthy peers, but they tend to make those errors more often and more repetitively. The findings suggest that arithmetic instruction for children with MM should focus on teaching them step-by-step algorithms that they can apply to specific types of problems (Ginsburg, 1997; Jordan & Montani, 1997). For children with TBI, the current results are more positive. The TBI group did not differ significantly from the OI group, suggesting that the basic computational skills of children with TBI are similar to those of healthy children. These results suggest that children who suffer a TBI will not experience significant computational deficits, at least not after the acute effects of the TBI have resolved.

Future research should expand upon the current study. Children with TBI should be examined closer to the time of their injuries and with measures of more complex mathematical skills. Although they do not appear to exhibit mathematical deficits several years after injury, they may experience difficulties acutely (Taylor et al., 2002). Children with TBI also may display difficulties with more complex forms of mathematics, such as fractions and decimals, geometry and algebra, and applied word problems. More generally, future research on the mathematical skills of children with brain disorders should incorporate measures of a broader range of mathematical skills, as well as measures that provide more qualitative information about the strategies children use to solve problems. Group profiles in complex mathematical skills and strategies may differ from those for computational arithmetic, as may their cognitive correlates. For instance, the stronger relationship found between visual-spatial skills and WRAT–3 performance in older children may have occurred because of their difficulties with fractions and algebraic equations, but specific measures of these types of mathematical problems are needed for a more detailed examination of this hypothesis. Finally, future research also should follow up on the developmental variations in cognitive correlates of arithmetic skills reported here. The interactions between age and processing speed, declarative memory, and visual-spatial skills warrant further exploration.

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