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# Arithmetic Processing in Children With Spina Bifida: Calculation Accuracy, Strategy Use, and Fact Retrieval Fluency

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# Arithmetic Processing in Children With Spina Bifida:

## Calculation Accuracy, Strategy Use, and Fact Retrieval Fluency

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### Abstract

Three studies compared 98 children with spina bifida myelomeningocele (SBM)—a disorder associated with high rates of math disability and spatial deficits—to 94 typically developing children on multidigit subtraction and cognitive addition tasks. Children with SBM were classified into those with reading decoding and math disability, only math disability, and no reading or math disability. Study 1 showed that visual–spatial errors in multidigit arithmetic were not elevated in children with SBM. In Study 2, deficits in accuracy, speed, and strategy-use in single-digit addition characterized groups with math disability regardless of reading status. Accuracy and speed on single-digit addition was strongly related to performance on multidigit subtraction. A math-level matching design in Study 3 revealed less mastery of math facts by the group with SBM. The results are discussed with reference to cognitive and neuropsychological models of math disability.

Math disability is a common learning disorder, occurring in 3% to 6% of the school-age population (Kosc, 1974; Shalev, Auerbach, Manor, & Gross-Tsur, 2000). Although numeracy skills are related to employment, wages, and productivity (Rivera-Batiz, 1992), less is known about the typical and atypical development of mathematical skills than is known about reading development. Even less research has been conducted on the developing cognitive and neural systems for math or on the correlates of math difficulties in children with neurodevelopmental disorders.

Some neurodevelopmental disorders, such as spina bifida myelomeningocele (SBM), fragile X syndrome, and Turner syndrome, are associated with elevated risk for problems in mathematics (Barnes et al., 2002; Mazzocco, 1998, 2001; Rovet, Szekely, & Hockenberry, 1994; Simon, Bearden, McDonald-McGinn, & Zackai, 2005; Wills, 1993). SBM is especially relevant to the study of learning disabilities (LD) because it is associated with a math disability in the absence of reading disability. About 25% of school-age children with SBM have a specific math disability (Fletcher et al., 2004), which is much higher than the incidence in the general population (Kosc, 1974; Shalev et al., 2000); in contrast, fewer than 3% of children with SBM show specific reading decoding problems (Fletcher et al., 2004). The uneven development of math and reading decoding skills in children with SBM is especially relevant to math disability models in which the nature of the math disability varies as a function of comorbid reading decoding problems (Geary, 1993; Rourke, 1993). This article presents three studies of mathematical processing in children with SBM that test cognitive–developmental math disability models.

## Spina Bifida Myelomeningocele

North America's most common severely disabling birth defect, SBM arises from a complex pattern of gene–environment interactions that produce a neural tube defect associated at birth with distinctive physical, neural, and cognitive consequences. The spinal cord defect produces an impairment of lower and upper extremity coordination, often with significant paraplegia and limited ambulation. SBM also involves significant disruption of brain development, which results in anomalies in the regional development of the brain, especially the corpus callosum, midbrain, and cerebellum. Additional injury to the brain arises from a blockage of cerebrospinal fluid flow due to a malformed cerebellum and hindbrain, resulting in hydrocephalus. Hydrocephalus disrupts not only the development of myelination but also cortical neuronal development, particularly in posterior brain regions (del Bigio, 1993).

Like the pattern of brain anomaly, cognitive development in SBM is uneven, with a modal profile of preserved and impaired cognitive and academic skills. As a group, children with SBM are stronger in language and weaker in visual–spatial and motor skills (Barnes & Dennis, 1998; Fletcher et al., 2004). Their math ability is impaired relative to their stronger word recognition skills, and writing problems are common (Barnes et al., 2002; Barnes, Dennis, & Hetherington, 2004; Fletcher et al., 2004). These difficulties persist into adulthood, with consequences for functional independence and quality of life (Dennis & Barnes, 2002). The impairment in visual–spatial skills is interesting, because neuropsychological models have proposed a relation between this domain and mathematical ability. Thus, visual–spatial skills may be important for the spatial organization and manipulation of numerical information (Geary, 1993; Kosc, 1974). A relation between deficits in math and visual–spatial processing has been proposed in SBM (e.g., Wills, 1993), although such relations have not been well documented.

## Cognitive and Neuropsychological Approaches to Math Disability

The presence or absence of a comorbid reading decoding disability is central to several models of math disability—particularly to those that grew out of a neuropsychological perspective (Rourke, 1993). Several early studies have shown that children with disorders of both word recognition and mathematics have a different cognitive profile from that of children with a more restricted mathematics disability (Morrison & Siegel, 1991; Rourke, 1993). Children with both reading decoding and math disability have been found to have deficits in verbal and visual working memory (Siegel & Ryan, 1989) and phonological processing (Swanson & Sachse-Lee, 2001). In contrast, children with specific mathematics disability have been found to have deficits in visual memory, visual–spatial working memory (McLean & Hitch, 1999; Siegel & Ryan, 1989), and visual–spatial function (Rourke, 1993; Share, Moffitt, & Silva, 1988). These studies of the neurocognitive correlates of math disabilities in different LD subtypes have provided little evidence about the nature of the mathematical disorder.

In contrast, recent studies have used the theories and research tools of cognitive development to understand mathematical processing in children with different forms of math disability. Such studies are concerned with the development of different mathematical processes in children with math disabilities and the underlying cognitive competencies associated with such processes (e.g., Geary, Hamson, & Hoard, 2000; Geary, Hoard, & Hamson, 1999). One math disability model (Geary, 1993) depicted deficits in math computation as arising from (a) problems in learning, representing, and retrieving math facts from semantic memory, a subtype hypothesized to be related to reading decoding disability through a common proposed deficit in phonological working memory and phonological processing, and thought to represent cognitive differences in mathematical processing in affected children; (b) difficulties in the acquisition and use of developmentally mature problem-solving strategies or procedures to perform mental or written calculations, a subtype in which the relation to reading decoding is not specified and that is thought to reflect developmental delays in mathematical processing; and (c) difficulties in the spatial representation and manipulation of number information, a less common subtype that is thought to characterize those individuals who have specific math impairment without reading decoding disability.

Research using these models has found that children with both reading decoding and math disabilities have the most pervasive problems in math (Geary et al., 1999; Hanich, Jordan, Kaplan, & Dick, 2001), experiencing difficulties in math fact retrieval, math concepts such as place value, word problem solving, and estimation. In contrast, children with only math disability have more circumscribed deficits: They are slow at retrieving math facts, suggesting imperfect math fact mastery, and they have difficulties in estimation and math concepts such as place value, although they perform better than children with reading decoding and math disability in language-related aspects of mathematics (e.g., counting, word problem solving; Hanich et al., 2001). Regardless of their reading decoding skill, children with math disability have persistent difficulty with math fact mastery (Jordan, Hanich, & Kaplan, 2003a, 2003b), which is somewhat unexpected in light of math disability models that propose direct links between deficits in math fact retrieval and phonological processing (e.g., Geary, 1993). Such findings have led to suggestions that math fact mastery may be related less to phonological processes and more to the manipulation of number along a "mental number line" (Jordan et al., 2003b), which is described as a semantic representation specific to quantity that captures relations between numbers in terms of size and distance (Dehaene, 1992; Dehaene, Piazza, Pinel, & Cohen, 2003).

The combination of math disability and specific neurocognitive deficits in children with SBM makes them an important population with which to test different models of mathematics disability. Of particular interest are children with SBM who have poorly developed visual–spatial skills and specific math disability, as they provide a strong test of the relation of specific math disability and visual–spatial processing, especially compared to children with SBM who have difficulties in visual–spatial processing but either have no learning disability or have both reading decoding and math disabilities. Children with SBM can also be used to test the generality of math disability models by asking whether the processing deficits associated with math disabilities in children without neurodevelopmental disorders are similar to those in disorders like SBM that are associated with significant perturbations of brain development.

To address these issues, math disability models were evaluated in three studies comparing typically achieving controls to children with SBM who have (a) specific mathematics disability; (b) both reading and mathematics disabilities; or (c) no learning disability. Study 1 tested math disability models by comparing math fact, procedural, and visual–spatial errors made by these groups in multidigit arithmetic. Study 2 compared the groups on math fact mastery to test hypotheses about the integrity of core mathematical processes in math disability subtypes. Study 2 also tested hypotheses about the relations between math fact mastery and multidigit arithmetic and between phonological skills, visual–spatial ability, and math fact mastery. Based on the findings from Study 2, Study 3 used a math-level matching design to test cognitive difference models against developmental delay models with respect to the nature of difficulties in math fact processing that characterize children with math disabilities.

## STUDY 1: WRITTEN SUBTRACTION

Calculation errors have been investigated in typically developing children (van Lehn, 1982), in adults with brain injury (Hartje, 1987), in neuropsychological studies of children with math disability (Strang & Rourke, 1985), and in children with acquired or congenital brain injury (Ashcraft, Yamashita, & Aram, 1992; Rovet et al., 1994). Calculation errors in typically developing children (van Lehn, 1982) have been classified as either fact-based in origin (i.e., an error due to the incorrect retrieval of math facts at the single-digit level) or procedural (i.e., incorrect application of an algorithm, such as borrowing from a zero). In addition to math fact and procedural errors, visual–spatial errors (i.e., errors due to misalignment of numbers in columns, misreading and miswriting of numbers, errors due to crowding of written work, and errors due to difficulties in visual attention) have been measured in neuropsychological studies.

Based on the model proposed by Geary (1993), three hypotheses were tested:

1. Children with SBM and good word decoding skills would make few math fact errors compared to children with poor word decoding skills, regardless of their mathematical skill level.
2. Children with both reading decoding and math disabilities would make more math fact errors than controls and than their peers with SBM who have no problems in reading decoding.
3. Computational errors of children with SBM would reflect problems in visual–spatial processing, regardless of their reading status.

## Method

### Participants

Children were recruited from Ontario and Texas as part of a research program on SBM. All the children were in Grade 3 or beyond. The children with SBM came from service-providing medical clinics in Houston, Toronto, London (Ontario), and Hamilton (Fletcher et al., 2004). Typically achieving control students from Texas and Ontario were volunteers who responded to announcements about the study. Comparisons of these English-speaking cohorts have shown no differences in sociodemographic characteristics, IQ, achievement, and other dimensions except for the higher number of Hispanics in Houston (Fletcher et al., 2004).

All children had at least one IQ score (either verbal or nonverbal) of 70 or higher on either the *Wechsler Intelligence Scale for Children–III* (WISC-III; Wechsler, 1991) or the *Stanford-Binet Intelligence Test–IV* (SB-IV; Thorndike, Hagen, & Sattler, 1986). These criteria were used to screen for overall intellectual deficiency. However, only a few children actually had both verbal and nonverbal IQ scores below 80. Different intelligence tests were used because participants came from two different studies that were combined to increase the sample size. For the control group, IQ was estimated from the SB-IV for 35 children and from the WISC-III for 59 children. For the children with SBM, IQ was estimated from the SB-IV for 89 children and from the WISC-III for 9 children. The Vocabulary subtests from the WISC-III/SB-IV and the Block Design (WISC-III) or Pattern Analysis (SB-IV) subtest were used as respective indicators of lexical language and visual–spatial skills for subsequent analyses.

Following procedures in both cognitive–developmental and neuropsychological studies (Fuchs & Fuchs, 2002), LD categories were determined by cutoff scores below the 25th percentile on standardized tests of word decoding (Letter–Word Identification from the *Woodcock-Johnson–Revised Tests of Achievement*; WJ-R; Woodcock & Johnson, 1989) and math computations (either Arithmetic from the *Wide Range Achievement Test–Third Edition* [WRAT-3]; Wilkinson, 1993; or Calculations from the WJ-R). Children with SBM with scores below the 25th percentile on both the reading decoding and math measures were considered to have both reading and math disability (RD + MD); children with scores below the 25th percentile on the math computation measure but above the 25th percentile on the reading decoding measure were considered to have a specific math disability (MD only); children with both reading decoding and math scores above the 25th percentile were considered to have no learning disability (NoLD). Control children (CON) had reading and math scores above the 25th percentile. These cut-points are conservative and should reduce effect sizes on dependent measures.

Table 1 shows the demographic data, IQ subtests, and achievement patterns for each group. Comparisons were made with ANOVAs. For significant group effects, post hoc analyses for all pairwise contrasts throughout the study were conducted using Fisher's protected least square difference (PLSD) controlling alpha at $p < .05$. The groups did not differ in age or grade at testing, although the group with RD + MD tended to be older. As expected, the groups differed in vocabulary. Table 1 shows that the groups with SBM had lower scores than the control group; the group with RD + MD had lower scores than both other groups with SBM, and the group with MD only had lower scores than the group with NoLD, $F(3, 188) = 25.5$, $p < .001$. The groups also differed in visual–spatial construction, $F(3, 188) = 29.5$, $p < .001$. The groups with SBM had lower scores than the controls, and the groups with RD + MD and MD only did not differ from each other but had lower scores than the group with NoLD. The groups differed in word decoding, $F(3, 188) = 51.1$, $p < .001$. The group with RD + MD had lower scores than every other group, and the group with NoLD had higher scores than the control group and the group with MD only, which did not differ from each other. The groups also differed in math achievement scores, $F(3, 188) = 109.6$, $p < .001$. The groups with SBM had lower scores than the control group, and the group with NoLD had higher scores than the groups with RD + MD and MD only, which did not differ from each other. Reading decoding was better developed than math calculation for all groups with SBM, $t(19) = -3.46$, $p < .01$, for the group with RD + MD; $t(30) = -11.25$, $p < .001$, for the group with MD; and $t(46) = -6.63$, $p < .001$, for the group with NoLD. Reading decoding and math calculation skills were comparably developed for the controls.

## Materials and Procedure

Children were tested individually in a quiet room. Each child was given a problem sheet with 20 multidigit subtraction problems and asked to solve as many problems as he or she could. Children had pencils with erasers and were told to show all of their work, with no time limits imposed. To test hypotheses about subgroup differences, a 20-item multidigit written subtraction task (van Lehn, 1982) with two- to five-column minuends (e.g., $64 - x$ to $64,974 - x$) and one- to four-column subtrahends (e.g., $y - 5$ to $y - 6,880$) was employed. Within this problem set, errors can be coded as reflecting problems related to the three math disability subtypes. We combined

**TABLE 1**
Means and Standard Deviations of Demographic Characteristics, by Group

| | SBM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | RD + MD[a] | | MD[b] | | NoLD[c] | | CON[d] | |
| Variable | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Age (months) | 157 | 32 | 144 | 26 | 148 | 37 | 142 | 26 |
| Grade | 6.6 | 2.5 | 5.8 | 2.1 | 6.2 | 3.0 | 6.1 | 2.1 |
| Gender (% girls) | 60 | | 55 | | 38 | | 50 | |
| WISC-III/SB-IV Vocabulary[e] | 20 | 15 | 37 | 26 | 51 | 23 | 65 | 24 |
| WISC-III Block Design/SB-IV Pattern Analysis[e] | 28 | 27 | 32 | 25 | 47 | 26 | 69 | 23 |
| WJ-R Letter–Word Identification[f] | 11 | 7 | 58 | 22 | 73 | 20 | 66 | 20 |
| WRAT-3 Arithmetic/WJ-R Calculations[e] | 5 | 6 | 12 | 8 | 52 | 22 | 67 | 20 |

*Note*. SBM = spina bifida myelomeningocele; RD + MD = both reading decoding and mathematics disabilities; MD = mathematics disabilities only; NoLD = no learning disabilities; CON = controls; WISC-III = *Wechsler Intelligence Scale for Children–Third Edition* (Wechsler, 1991); SB-IV = *Stanford-Binet Intelligence Test–Fourth Edition* (Thorndike, Hagen, & Sattler, 1986); WJ-R = *Woodcock-Johnson–Revised Tests of Achievement* (Woodcock & Johnson, 1989); WRAT-3 = *Wide Range Achievement Test–Third Edition* (Wilkinson, 1993).
[a] *n* = 20. [b] *n* = 31. [c] *n* = 47. [d] *n* = 94. [e] percentiles. [f] percentiles based on age.

error coding methods from developmental and neuropsychological studies to code math fact, procedural, and visual–spatial errors as follows:

1. math fact retrieval errors, reflecting an error on single-digit subtraction within the multidigit problem;
2. procedural errors, reflecting the misapplication of arithmetic procedures, such as problems in borrowing from zero; and
3. visual–spatial errors, reflecting problems in visual–spatial processing or visual attention.

Examples of these error types can be found in Figure 1 (see Notes 1 and 2).

This task also affords the opportunity to code two different classes of procedural errors—*slips* (i.e., procedural errors occurring only once despite at least two opportunities to make the same error, suggesting imperfectly consolidated knowledge of procedures or lapses in attention) and *bugs* (i.e., procedural errors occurring at least twice, assumed to reflect a lack of procedural knowledge).

The number of problems solved correctly and the number of errors were recorded. Fact retrieval errors and procedural bugs and slips were coded using van Lehn's detailed error scoring method, called the *Subtraction Bug Glossary* (van Lehn, 1982), which was revised based on Hartje (1987) to include visual–spatial errors. Errors in visual attention reflecting difficulties in attention monitoring were added to this category (see Figure 1). Errors were scored by two coders. Agreement between coders was 96% on general categories of errors (math fact, procedural, and visual–spatial). Discrepancies between the two coders were resolved through discussion of the errors in relation to the coding manual, so that 100% agreement was achieved at the level of these general error categories. Differences between coders in identifying specific procedural errors that were important for coding slips versus bugs (e.g., whether difficulties with borrowing on two different problems reflected exactly the same type of borrowing error or not) were also resolved by discussion about which procedural code best fit the error according to the detailed scoring rules laid out in the bug glossary. Any discrepancies in procedural codes were able to be resolved in this manner. On most items, a single error was coded. However, multiple coding was done where appropriate (e.g., if both procedural and math fact errors were made in the same problem).

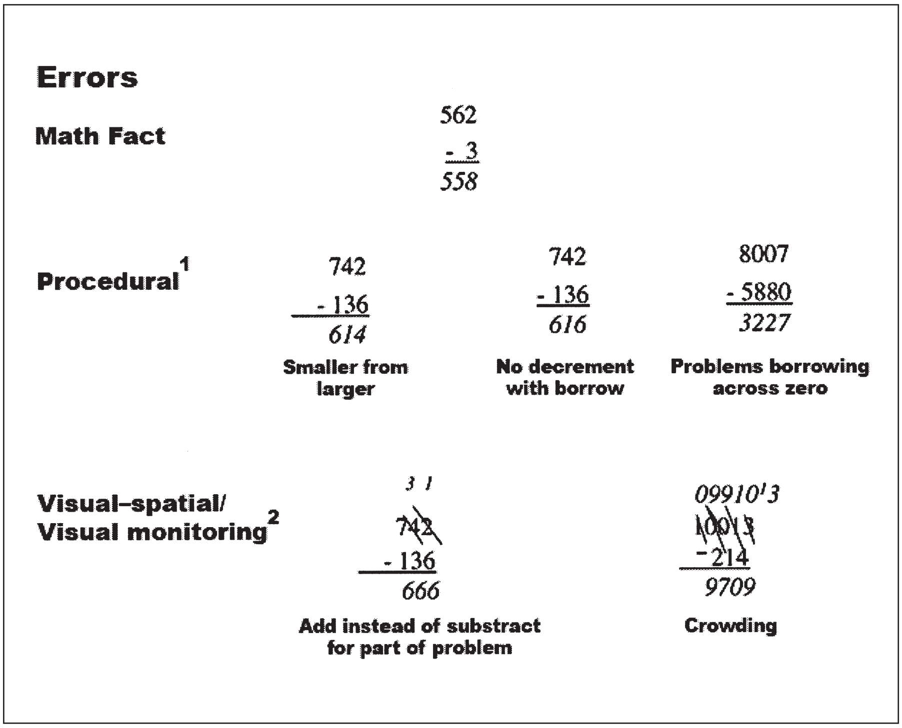

**FIGURE 1.** Examples of subtraction errors. *Note.* The superscripts 1 and 2 in the figure refer to Notes 1 and 2 at the end of this article.

## Results

Table 2 shows that all groups with SBM correctly solved fewer subtraction problems than controls, $F(3, 188) = 47.12$, $p < .001$. Fisher's PLSD tests revealed that the group with NoLD had significantly higher scores than the two groups with MD, and the group with MD only had significantly higher scores than the group with RD + MD. Although most children attempted most problems, groups differed in how many problems were attempted, $F(3, 180) = 6.25$, $p < .001$. The group with RD + MD attempted fewer problems (84%) than the control group (99%) and the group with NoLD (95%), and the group with MD only attempted fewer problems (88%) than controls. Twenty-six participants completed fewer than 20 questions; 20 of these participants completed enough questions to reliably discriminate between bugs and slips (6 to 19 questions).

Three types of errors were analyzed in a one-way MANOVA, revealing a significant group effect, $F(3, 186) = 21.43$, $p < .001$. Post hoc analyses using Fisher's PLSD showed that the groups differed in the number of math fact errors, with the group with RD + MD making this type of error more often than the control group. The groups also differed in the number of procedural errors, with all groups with SBM making more procedural errors than the control group, and the group with RD + MD making more procedural errors than the group with NoLD. No significant differences were found between any of the groups in visual–spatial errors.

**TABLE 2**
Study 1: Means and Standard Deviations for Written Subtraction Results by Group

| | SBM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | RD + MD[a] | | MD[b] | | NoLD[c] | | CON[d] | |
| Variable | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| Number correct out of 20 | 5.4 | 5.6 | 9.1 | 6.4 | 13.0 | 6.4 | 17.5 | 3.0 |
| Math fact errors[e] | 1.4 | 1.5 | 0.7 | 1.7 | 0.7 | 1.9 | 0.6 | 0.9 |
| Procedural errors[e] | 9.7 | 7.5 | 9.1 | 6.9 | 6.5 | 7.3 | 1.9 | 3.1 |
| Visual–spatial/visual monitoring errors[e] | 0.6 | 0.8 | 0.5 | 0.8 | 0.4 | 0.8 | 0.3 | 0.6 |
| Bugs | 1.8 | 1.9 | 1.6 | 1.4 | 0.9 | 1.3 | 0.3 | 0.8 |
| Slips | 2.5 | 2.7 | 1.9 | 2.4 | 1.6 | 1.9 | 0.8 | 1.1 |

*Note.* SBM = spina bifida myelomeningocele; RD + MD = both reading decoding and mathematics disabilities; MD = mathematics disabilities only; NoLD = no learning disabilities; CON = controls.
[a] $n = 20$. [b] $n = 31$. [c] $n = 47$. [d] $n = 94$. [e] error frequency.

Procedural errors (bugs and slips) were further analyzed using ANOVAs. There was a group effect for both bugs, $F(3, 180) = 13.92$, $p < .001$, and slips, $F(3, 180) = 6.99$, $p < .001$. All groups with SBM had more bugs and slips than the control group. Within the groups with SBM, the groups with RD + MD and MD only had more bugs than the group with NoLD, but all groups with SBM made similar numbers of slips.

## STUDY 2: COGNITIVE ADDITION

Error analyses like those in Study 1 measure accuracy, but a skill is mastered only when its performance is both accurate and fluent. Some theorists propose that math fact mastery may be important for the development of more complex arithmetic skills as well as for the development of some other aspects of math (Geary, 2003). For example, fluent math fact retrieval may free cognitive resources to learn and perform more complex mathematical operations. To investigate math fact retrieval processes in children with SBM, a cognitive addition task commonly used in developmental and cognitive studies of mathematical cognition (e.g., Ashcraft, 1992; Siegler, 1987) was employed to look at computational accuracy, fluency, and strategy use.

Three questions about math fact retrieval were addressed in Study 2. The first concerns the status of math fact retrieval processes in good and poor word decoders with math difficulties. Groups with SBM and either RD + MD or MD only were compared to the controls and the group with SBM and NoLD. According to the subtyping model, fact retrieval processes should be intact in good decoders with SBM but deficient in poor decoders with SBM, because of the underlying deficit in phonological processing for reading and math fact retrieval in poor decoders. However, recent studies of children with math LD without neurological disorder suggest that math fact mastery may not be entirely intact regardless of reading status (Hanich et al., 2001; Jordan et al., 2003a).

The second question concerns the contribution of math fact mastery to more complex aspects of math as discussed earlier—specifically, whether accuracy and speed in solving single-digit arithmetic problems was related to performance on written multidigit arithmetic problems. In other words, how well does the variability in math fact retrieval processes predict the variability on computational tasks involving multidigit arithmetic?

The third question concerns the contribution of phonological skills and visual–spatial skills to math fact mastery. Competing hypotheses about the nature of the representation underlying math fact mastery were tested. In one view, difficulties in math fact retrieval are related to language-based processes involved in the representation and retrieval of phonological information from semantic memory (Geary, 1993). An alternate view is that math fact retrieval deficits are specific to the domain of number or quantity and involve difficulties in manipulating nonverbal representations such as might be encountered were a mental number line to be implicated in the solving of single-digit arithmetic problems (Jordan et al., 2003b). The contribution of math fact mastery to multidigit, written arithmetic and the contribution of phonological and visual–spatial skills to math fact mastery were tested using regression models.

### Method

#### *Participants*

The participants were identical to those employed in Study 1, except that data from one participant in the group with RD + MD was lost due to equipment malfunction.

### Materials and Procedure

Forty single-digit addition problems were composed using digits from 1 to 9. There were no repetitions of problems such as 3 + 4 and 4 + 3. The larger and smaller digits were each presented first on half of the problems.

The task was run on an IBM compatible computer using a program written in Micro Experimental Laboratory (MEL) that presented the stimuli and recorded responses. The instructions appeared on the screen and were read to the participant. When the child understood the task, the examiner pressed a key on the MEL response box that resulted in the presentation of an addition problem. Problems were presented in a set order in horizontal format (e.g., 3 + 4 = ?) in the center of a 16-inch diagonal View Sonic computer screen. Participants had to say the answer as quickly but as accurately as they could into a microphone that activated the voice-operated relay connected to the computer. Responses were timed from the onset of the problem on the screen to the onset of the response, at which point the problem disappeared from the screen.

While the child solved the problem, the examiner recorded the strategy she observed the child using and, after each response, asked the child what strategy he or she used to solve the problem. Strategy use was coded in sequence from most to least developmentally mature as follows: (a) *direct retrieval* (the child just knew the answer for 3 + 4 was 7); (b) *counting up* or *min strategy* (the child counted up from the highest number: 4, 5, 6, 7); (c) *counting all* or *sum strategy* (the child counted 1, 2, 3, 4, 5, 6, 7). Finger counting and verbal counting were also recorded, as were other strategies reported by the students or observed by the examiner. For example, the child might report using *decomposition*, which is not observable to the examiner (e.g., on a problem such as 6 + 5, the child might report adding 5 + 5 + 1). Following typical procedures in cognitive addition paradigms, examiners queried two types of responses: (a) long response trials, where the child did not overtly use fingers or verbal counting, and on which direct retrieval was reported; and (b) trials on which the examiner observed a particular strategy, such as counting up, but another strategy, such as direct retrieval, was reported. After the strategies were recorded, the examiner pressed one of two keys on the MEL response box that indicated whether the participant's response was correct or incorrect. The next problem immediately appeared on the screen.

The strategy identification and coding procedures are those typically used in studies that employ the cognitive addition paradigm (e.g., Ashcraft, 1992). Trials on which there was participant–examiner agreement in strategy use were used in the analyses, so that mean response times were computed for each participant for each type of strategy. Examiner and participant strategy reports were identical 82% of the time for the group with RD + MD, 84% for the group with MD only, 88% for the group with NoLD, and 87% for the controls. Trials on which the examiner coded a direct retrieval trial, but the child reported using a strategy such as decomposition or counting up with no overt signs of counting were also used in the analyses, and these were coded as reflecting the strategy provided by the child. With the addition of trials on which the child's strategy was not observable (e.g., examiner coded direct retrieval, but child used decomposition), agreement between participant and experimenter reached 99% for all groups. Trials on which the examiner observed a particular strategy but the child reported using a different strategy even after querying were not used in the analyses.

For the purposes of this article, responses for $N + 0$ and $N + 1$ trials were not analyzed (see Baroody & Tiilikainen, 2003, for a discussion). Only correct trials were used in the analyses of response time. Because there were relatively few counting all and decomposition trials for some groups, response times for these strategies were not compared. Two of the participants in the group with RD + MD had too few direct retrieval trials to analyze their direct retrieval response times.

## Results

### Accuracy

The groups differed in accuracy in solving single-digit addition problems, $F(3, 187) = 5.97$, $p < .001$. Table 3 shows that the two groups with SBM and MD were less accurate than the control group and the NoLD group, which did not differ from each other.

### Strategy Choice

Finger counting was used very infrequently in any group and was not analyzed separately from verbal counting. Strategy use (direct retrieval, counting up, counting all, and decomposition) was analyzed using MANOVA. There was a significant group effect, $F(4, 186) = 17.89$, $p < .001$. Post hoc analyses using Fisher's PLSD showed that controls used more direct retrieval than groups with SBM, the group with NoLD used more direct retrieval than the two SBM groups with MD, and the group with MD only used more direct retrieval than the group with RD + MD. The groups also differed in counting up, but the pattern of results was opposite to that for direct retrieval: The control group used less counting up than the groups with SBM, the group with NoLD used less counting up than the two groups with MD, and the group with MD only used less counting up than the group with RD + MD. There were no significant differences between groups in counting all or decomposition strategies.

### Response Time

Only response times for direct retrieval and counting-up trials are reported. Direct retrieval trials were divided into small and large problems, with *small*

**TABLE 3**
Study 2: Means and Standard Deviations for Cognitive Addition Results, by Group

| | SBM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | RD + MD[a] | | MD[b] | | NoLD[c] | | CON[d] | |
| Variable | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| % Correct | 79.5 | 14.1 | 80.6 | 13.0 | 87.0 | 9.9 | 87.3 | 8.1 |
| % Direct retrieval | 44.7 | 24.8 | 61.1 | 26.4 | 73.6 | 24.9 | 81.8 | 17.1 |
| % Count-up | 48.2 | 29.1 | 32.0 | 23.1 | 19.2 | 21.8 | 11.2 | 15.5 |
| % Count all | 3.5 | 9.7 | 3.5 | 12.6 | 2.9 | 15.2 | 0.9 | 8.6 |
| % Decomposition | 2.8 | 9.0 | 3.4 | 7.3 | 3.8 | 6.5 | 6.1 | 8.8 |
| Direct retrieval RT (ms) | | | | | | | | |
| Small sum | 1,750 | 712 | 1,475 | 441 | 1,301 | 453 | 1,060 | 292 |
| Large sum 1,704 | 588 | 1,705 | 725 | 1,434 | 570 | 1,235 | 390 | |
| Count-up RT (ms) | 4,836 | 2,217 | 4,134 | 2,037 | 3,938 | 1,988 | 3,273 | 1,750 |

*Note*. SBM = spina bifida myelomeningocele; RD + MD = both reading decoding and mathematics disabilities; MD = mathematics disabilities only; NoLD = no learning disabilities; CON = controls; RT = response time.
[a] *n* = 19. [b] *n* = 31. [c] *n* = 47. [d] *n* = 94.

problems summing to less than 10 and *large* problems summing to 11 or more. Response times for small problems are typically shorter (the problem size effect), which reflects the fact that smaller problems are encountered more frequently and at early ages than larger problems (Siegler, 1988). Direct retrieval trials (small sum and large sum) were analyzed using MANOVA, revealing a significant group effect, $F(3, 181) = 18.26$, $p < .001$. Post hoc analyses showed that for small-sum trials, the groups with SBM were slower than controls, and the group with RD + MD was slower than both other groups with SBM. For large-sum trials, the groups with SBM were slower than the control group, and the group with MD only was slower than the group with NoLD.

An ANOVA revealed a significant group effect for counting-up trials, $F(3, 123) = 3.20$, $p < .05$, with the group with RD + MD slower than the control group (see Table 3).

### *Math Fact Mastery and Multidigit Arithmetic*

To test the hypothesis that math fact mastery is related to performance on more complex arithmetic operations, age at testing, accuracy on cognitive addition, and response time on direct retrieval trials were used to predict accuracy on the written subtraction task from Study 1 using all participants with SBM and all control children. The model predicted 40% of the variability in written subtraction scores, $F(3, 184) = 41.9$, $p < .001$, with significant contributions of accuracy, $t = 3.56$, $p < .001$, and retrieval speed, $t = –8.27$, $p < .001$.

### *Phonological Skill, Visual–Spatial Skill and Math Fact Mastery*

To test the hypothesis that phonological or visual–spatial skills may be related to math fact mastery, visual–spatial skill (SB-IV Pattern Analysis or WISC-III Block Design) and phonological skill (WJ-R Word Attack) were used to predict cognitive addition accuracy and math fact fluency (response time on direct retrieval trials) using all participants with SBM and all control children. The model predicted 10% of the variability in cognitive addition accuracy, $F(2, 189) = 11.74$, $p < .001$, with significant contributions of spatial skill, $t = 2.5$, $p < .05$, and phonological decoding, $t = 3.16$, $p < .01$. The model predicted 13% of the variability in math fact fluency, $F(2, 185) = 14.95$, $p < .001$, with significant contributions of both visual spatial skill, $t = –2.4$, $p < .05$, and phonological decoding, $t = –3.95$, $p < .001$.

## STUDY 3: MATH-LEVEL MATCHING

Study 3 tested whether difficulties in math fact mastery (accuracy and speed in single-digit arithmetic) represented cognitive differences or developmental delays in mathematical processing. The cognitive addition task was chosen for the math-level matching comparisons for two reasons. First, because deficits in math fact mastery are hypothesized to constitute cognitive differences in children with and without math difficulties (Geary, 1993; Russell & Ginsburg, 1984), a paradigm that measures these math fact retrieval processes is important for testing cognitive difference versus developmental delay models of the relation between math fact mastery and math disability. Second, the cognitive addition paradigm also allows the testing of those aspects of math that involve strategy use. Children's difficulties in both strategy use in single-digit arithmetic and knowledge and application of arithmetic algorithms in multidigit arithmetic are presumed to represent developmental delays rather than cognitive differences in mathematical performance (Geary, 1993).

One way to test hypotheses related to cognitive differences and developmental delays is to compare mathematical processing in children with math difficulties who are matched for level of math achievement to younger, typically developing children. The logic behind such comparisons is that if older children with LD demonstrate learning strategies and cognitive processes that are similar to those of younger, typically developing children, then the skills of the child with LD are delayed, but not different in kind, from those used by typically developing children. On the other hand, if the learning strategies and cognitive processes of older children with LD differ from those of younger, typically achieving children, then this would constitute evidence for a cognitively distinct deficit in math. Achievement level matching designs have commonly been used in reading studies (Backman, Mamen, & Ferguson, 1984; Oakhill, 1993; Stanovich & Siegel, 1994) and reading comprehension studies and less frequently in math studies (but see Barnes et al., 2002; McLean & Hitch, 1999; Russell & Ginsburg, 1984). Thus, for Study 3, older children with SBM were compared on the cognitive addition task to mathematics level–matched younger controls. We expected that children with SBM would differ from controls in how quickly they retrieved addition facts from memory, reflecting a cognitive difference in their mathematical processing, but that the groups would not differ in those aspects of mathematical processing that are assumed to reflect developmental delays, namely, their use of computational strategies.

## Method

Children with SBM and control participants were drawn from the groups in Study 2. Children with SBM were matched to controls on the basis of their grade level on a standardized math achievement test (either Arithmetic from the WRAT-III or Calculations from the WJ-R). Pairs of children with SBM and controls were matched using the same math achievement test, in order to control for possible differences between tests in the estimation of grade equivalents. In both groups, only children with no reading decoding disability were used, and math status was free to vary.

From the overall sample, 67 children with SBM and 67 controls could be matched on the math-level variable, with participants ranging in age from 92 to 222 months. As expected, the group with SBM was significantly older than the control group (149 vs. 133 months), $t(66) = 4.91$, $p < .001$. The mean actual grade placement of the control group was fifth grade; the mean grade placement of the group with SBM was sixth grade, $t(66) = 3.56$, $p < .001$. The average grade achievement in math was Grade 5 for both groups, meaning that the group with SBM was delayed in math by about 1 year. The group with SBM scored at the 40th percentile on the math achievement test; the control group scored at the 62nd percentile. Both groups were, on average, grade-appropriate readers—at the 72nd and 71st percentiles for the group with SBM and the control group, respectively, for Letter–Word Identification, and at the 58th and 60th percentiles on Word Attack, meaning that the group with SBM was at a higher grade level in reading than the controls. The group with SBM had significantly lower verbal IQ (50th versus 66th percentile) and nonverbal IQ (43rd versus 64th percentile) scores than the control group, consistent with the findings in Study 1. There were 35 girls in the group with SBM, and 31 girls in the control group. The data from the cognitive addition task in Study 2 were used for the comparisons.

**TABLE 4**

Study 3: Means and Standard Deviations for Cognitive Addition Results for Math-Level Matching Comparisons

| | SBM | | CON | |
|---|---|---|---|---|
| Variable | *M* | *SD* | *M* | *SD* |
| % Correct | 85.5 | 10.3 | 86.4 | 8.2 |
| % Direct retrieval | 71.6 | 23.6 | 77.8 | 17.0 |
| % Count-up | 22.9 | 22.4 | 13.6 | 15.6 |
| % Count all | 0.8 | 4.5 | 1.3 | 10.2 |
| % Decomposition | 4.2 | 7.2 | 7.2 | 10.2 |
| Direct retrieval RT (ms) | 1,405 | 493 | 1,279 | 412 |
| Count-up RT (ms) | 3,916 | 2,062 | 3,446 | 2,247 |

*Note*. SBM = spina bifida myelomeningocele group; CON = control group; RT = response time.

## Results

Analyses on addition fact accuracy, speed, and strategy use were conducted using paired *t* tests; they are summarized in Table 4. The results are given with no correction of alpha for number of comparisons, as we also report Cohen's *d* statistic, given that the key issue in achievement level matching designs concerns the size of the effect. There were no differences between groups in addition accuracy (86% for both groups). Comparisons of strategy use revealed the following results: counting up, $t(66) = 2.81, p < .007, d = -.48$; memory retrieval, $t(66) = -1.9, p < .07, d = .30$; and decomposition, $t(66) = -1.86, p < .07, d = .34$. Comparison of response times on direct retrieval trials (averaging small- and large-sum trials) produced the following results: $t(65) = 2.18, p < .04, d = .28$.

## DISCUSSION

The three studies present findings on mathematical processing in a neurodevelopmental disorder, SBM, that is associated with a high rate of math difficulties, relatively better preserved reading ability, and deficits in some but not all of the cognitive skills hypothesized to support math competence. Subgroups of good and poor readers within the population of children with SBM allowed us to test core hypotheses from cognitive and neuropsychological models of math disability as well as to test the power of these models for predicting the nature of mathematical processing deficits in children with significant perturbations in brain development.

Differences in mathematical processing were evident between children with SBM and math difficulties with and without reading decoding disability. In keeping with predictions based on the subtyping model discussed earlier (Geary, 1993), only the group with SBM and RD + MD made more math fact retrieval errors than typically developing children with good word decoding skills on a test of multidigit subtraction in Study 1.

In contrast to predictions from the subtyping model and from neuropsychological hypotheses, there was no evidence for visual–spatial dyscalculia in children with SBM and MD only—a group with known deficits in visual–spatial processing associated with their anomalous brain development. Even in the groups with the most severe visual–spatial deficits, these children did not make visual–spatial errors in their written multidigit calculations. Children with SBM have neither the visual–spatial form of dyscalculia of some adults with acquired brain injuries nor the visual–spatial subtype of math disability, in which visual–spatial deficits are observed on mathematical processing tasks. Furthermore, although visual–spatial skill and math fact mastery were related in the regression analyses, that relationship was relatively small. The fact that groups with poor visual–spatial skills also have a greater incidence of math difficulties is sometimes taken as evidence for a possible relation between the two (e.g., Jordan et al., 2003b; Rourke, 1993). However, more direct tests of this relation in both typically and atypically developing individuals have often yielded null results (Barnes, Smith-Chant, & Landry, 2005; Rovet et al., 1994; but see Mazzocco, 1998). More research should be completed addressing a broader array of visual processing skills and math domains, such as geometry, that more clearly require visual–spatial skills (Barnes et al., 2002).

The group differences in accuracy in multidigit subtraction in Study 1 are relevant to a characterization of mathematical performance in children with math difficulties. The group with RD + MD did not differ from the group with MD only on the standardized math test, but they showed poorer performance on the experimental written subtraction task. In some cases, tasks derived from theories of mathematical processing may be more sensitive indicators of mathematical difficulties than standardized measures (Ashcraft et al., 1992; Ginsburg, Klein, & Starkey, 1998). Although the group with RD + MD differed in accuracy from the group with MD only, both groups made more procedural errors than children with SBM who had no math disability. This finding suggests that in multidigit calculation, children with math difficulties have poorer procedural knowledge than children without math disabilities, regardless of their reading status or the presence of a neurological disorder.

Children with SBM and MD made more procedural errors than children with SBM who had no LD, but these differences occurred at the level of bugs, not slips. That is, *all* children with SBM made similar numbers of slips, and they made more slips than controls. Attention difficulties are common in children with SBM (Fletcher et al., 2004). In children with no brain injury, there is overlap between attention-deficit disorder (ADD) and learning disabilities, although relatively little is known about how ADD might affect mathematical processing. It is interesting to consider whether the elevated rate of procedural slips for children with SBM is related to attention difficulties and, if so, whether this finding would generalize to other groups of children with difficulties in both math and attention.

The findings on accuracy in written subtraction for the group with SBM and RD + MD are in keeping with other studies of children with comorbid reading decoding and math disabilities, who have the most severe and pervasive difficulties in math (Fuchs & Fuchs, 2002; Hanich et al., 2001). In the current study, the group with RD + MD showed poorer performance on the experimental written subtraction task than the group with MD only and made more math fact errors than the control group. On the cognitive addition task, they used a less mature mix of strategies than other groups, they used counting strategies on more than half of the trials, and they were slower than the groups with no LD even on those trials on which they directly retrieved the answer from memory. Also, children with RD + MD were slower than children with MD only in retrieving answers to small-sum problems. These results for single-digit addition, combined with the increased incidence of both math fact and procedural errors in the multidigit calculation performance of children with RD + MD, suggest that the sources of their difficulties in calculation may be multifaceted.

Although there are differences between the RD + MD and MD-only groups with SBM, one similarity is striking: The two groups with math disabilities did not differ from each other and were less accurate than children with no math disability on single-digit addition. They were also slower than children with no math disability on the direct retrieval of math facts. These findings are consistent with those from recent studies of children with no brain injury who had math disabilities (Jordan et al., 2003a, 2003b). Study 2 showed that the presence of significant developmental brain anomalies does not change the fundamental finding that math fact mastery is disturbed in children with math difficulties. Such consistency in findings across different groups of children with math disability—some with frank brain injury and others without—provides constraints on LD models and converging evidence for core deficits in math disability subtypes.

Consistent with the math disability model of Geary (1993), children with SBM and no LD were as accurate as their typically developing peers in solving single-digit addition problems. However, the strategy use and response time results tell a somewhat more complex story: Children with SBM in all groups used less mature strategies to solve problems. Even when directly retrieving answers from memory, they were slower than controls. These results are not consistent with the hypothesis that difficulties in math fact retrieval and word recognition share a common underlying deficit in phonological processing or phonological working memory (Geary, 1993). First, the group with MD and intact word recognition and phonological processing skills also had deficits in all aspects of math fact mastery. Although the group with SBM and no LD had better word decoding ability than controls, they were less skilled in strategy use and math fact fluency compared to controls. The results for the group with SBM and no LD demonstrate that high levels of word decoding and phonological skills do not necessarily go hand in hand with highly developed math fact mastery (see also Jordan et al., 2003b). This partial separation of word decoding and phonological skills from math fact mastery suggests that the two skills engage partially segregated cognitive processes.

Some researchers have suggested that deficits in math fact retrieval might constitute a cognitive difference in mathematical processing in children with math disabilities. In contrast, difficulties in other aspects of arithmetic, such as the correct use of procedures in multidigit computation and the use of developmentally mature strategies in single-digit arithmetic, might reflect developmental delays. Thus, children with math disabilities would be similar to younger, typically developing peers in their use of computational strategies and procedures, but they might differ in math fact fluency (Geary, 1993; Russell & Ginsburg, 1984). Testing these hypotheses by matching older children with SBM to younger, typically developing children for grade level in calculation, and then comparing their patterns of performance in cognitive addition, yielded somewhat surprising results. The groups did not differ on accuracy, and although there was a small group effect for the speed with which math facts were directly retrieved from memory, the effect sizes for strategy use ranged from small to medium, with older children with SBM using less developmentally mature strategies (i.e., counting up) than their younger controls. These findings show that children with SBM use slower backup strategies on more problems than younger, typically developing children—a difficulty that has been presumed to represent a developmental delay rather than a cognitive difference in arithmetic processing.

In strategy choice models (e.g., Shrager & Siegler, 1998), the use of backup strategies is assumed to reflect the learning history of the individual—either less frequent exposure to a particular problem, or later order of acquisition of a particular problem, with larger problems being less frequent and exposure occurring at a later point than for smaller problems (Campbell & Graham, 1985). A different mechanism may be at play for children with SBM, including those without RD or MD, which could relate to their difficulties in suppressing irrelevant information in semantic memory. Although children with SBM have no difficulty activating semantic information during reading, they do have problems suppressing contextually irrelevant information over time (Barnes, Faulkner, Wilkinson, & Dennis, 2004). A similar situation may apply to math fact retrieval: If solutions to closely associated math fact problems (e.g., 3 + 5 when solving 3 + 4) remain activated during retrieval of the solution, there may be more reliance on backup strategies to ensure accuracy, and there may be more interference from closely associated problems in memory, which could slow retrieval. This explanation of why children with SBM, even those with no MD, seem to have a higher confidence criterion for solving single-digit arithmetic problems remains to be tested.

Math-level matching designs can be criticized on the same grounds as reading-level matching designs, especially in inferring causal relations, as they are prone to artifacts involving regression to the mean (Backman et al., 1984). However, they are useful in investigating different patterns of cognitive processing between groups (Stanovich & Siegel, 1994). In this study, we used the math-level matching design to evaluate differences in aspects of math fact mastery in children who have asynchronous development of reading and math compared to typically developing children. We do not know the causes of those differences.

The regression analyses that used accuracy and speed of math fact retrieval demonstrated that math fact mastery is strongly related to more complex arithmetic problem solving. Cognitive addition accuracy and the speed of retrieval of addition facts from memory accounted for 40% of the variability in performance on multidigit subtraction, even though children made few math fact errors in written subtraction. The fluency of these basic computational processes at the single-digit level may be important for freeing resources during more complex computations, so that more attention can be devoted to learning and performing arithmetic procedures and math problem solving.

There are several different views about what might cause deficits in number fact retrieval. These include deficient phonological representations—particularly in phonological memory—that pose problems for learning and retrieving math facts as well as for reading (Geary, 1993); problems in inhibiting closely related math facts in memory (Geary, 2003); slow information processing across cognitive domains, including math (Bull & Johnston, 1997); and difficulties in manipulating nonverbal representations (Jordan et al., 2003b). The data in these studies can be used to address several of these hypotheses. First, the children with SBM and no LD, who were actually better word decoders than typically developing children, nonetheless had less well developed math fact mastery. Second, both phonological and visual–spatial skills were related to math fact mastery, although both accounted for relatively little variance in number fact performance. Third, the math-level matching comparison showed that differences in both strategy use and speed characterized deficits in math fact mastery, and we suggested that difficulties in suppressing irrelevant information in memory might play a role in the choice of backup strategies and slower memory retrieval. Fourth, children with MD only had an advantage over children with RD + MD in speed of retrieving answers to small-, but not large-sum problems, suggesting that their better phonological skills may support the storage and retrieval of small, exact addition facts in rote verbal or phonological memory (Dehaene et al., 2003). The data do not, however, provide definitive answers about the nature of the cognitive representations that underlie number facts or about whether deficits in math fact mastery reflect causes or outcomes of mathematical difficulties (see Torgesen, Rashotte, & Alexander, 2001, for a discussion of this issue as it relates to reading fluency). Longitudinal studies will be important for investigating what some of the causal relations might be between the development of various phonological skills, visual–spatial processing, fine motor ability (Barnes et al., 2005; Butterworth, 1999), and basic arithmetic skills. Conditions such as SBM, in which there is a known risk for math disability from birth, may prove to be particularly useful in this endeavor.

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## AUTHORS' NOTE

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## NOTES

1. *In theory, the ability to distinguish between math fact errors and errors due to miswriting or misreading numbers (coded as visual errors) would appear to be difficult. In practice, math fact errors typically differ from the correct answer by 1, suggesting the retrieval of a closely associated but incorrect math fact: in the first example of Figure 1, 12 – 3 = 8 instead of 12 – 3 = 9. Errors due to misreading or miswriting numbers were very rare. Examples would be (a) writing a 6 when the answer is 9; or (b) writing 48 as the answer to 79 – 28, where 79 was misread as 76.*
2. *The distinction between certain visual and procedural errors is related to the context in which the error occurs. The first example of a visual error in Figure 1 was coded as such because the child added instead of subtracted the middle column in only one problem. Had the child consistently added the middle column of each subtraction problem, the error would be procedural.*

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