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Processing Abilities Associated with Math Skills in Adult Learning Disability

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This study evaluated college adults (N = 138) referred for learning problems using a Cattell-Horn-Carroll based intelligence measure (Woodcock Johnson-Revised: WJ-R) and spatial and executive function neuropsychological measures to determine processing abilities underlying math skills. Auditory and visual perceptual (WJ-R Ga and Gv), long- and short-memory (WJ-R Glr and Gsm), crystallized and fluid intellectual (WJ-R Gc and Gf), and spatial and executive function (Judgment of Line Orientation [JLO] and Category Test) measures differentiated those with and without math deficits. Multiple regression revealed selective processing abilities (Gf, JLO, and Category) predicting about 16% of the variance in math skills after variance associated with general intelligence (also about 16%) was removed. Cluster analysis found evidence for a selective spatial deficit group, a selective executive function deficit group and a double deficit (spatial and executive function) group. Results were discussed in relation to a double deficit hypothesis associated with developmental dyscalculia.

It has been widely noted that math learning disability has not been extensively studied (Badian, 1983; Floyd, Evans, & McGrew, 2003; Geary, 1993; Strang & Rourke, 1983). However, existing research suggests two important areas of investigation that may inform our knowledge of the cognitive components underlying math disability. First, although some evidence suggests that mathematical ability consists of at least two neuropsychological abilities (spatial ability and executive functions), to what extent are these processes overlapping? Second, are there additional cognitive processing disorders that underlie mathematical ability? Examination of these issues is vital to informing our understanding of the cognitive components and potential treatment of math disability.

Floyd, et al. (2003) have noted a rather circumscribed approach to identifying the cognitive processing disorders underlying math achievement. For example, they identified a “specification error” in extant research in which important intellectual factors have been unexamined in studies attempting to specify the processing disorders underlying poor math achievement. For example, Geary’s (1993) widely cited review of math disability clearly states that the review of research is confined to “lower order numerical skills” and does not consider the role of higher order cognitive processes such as executive function. Likewise, in the testing of Dinnel’s model of math ability, Batchelor, Gray, & Dean (1990) note that the model is constrained to dealing with math skills in a situation where continuous visual processing of task-related information is present, such that memory retrieval and some aspects of problem solving skills are minimized. In an attempt to deal

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with such limitations, Floyd et al. (2003) used a Cattell-Horn-Carroll model of intelligence, instantiated by the Woodcock-Johnson battery, to evaluate processing abilities underlying math skill development from the standpoint of all factor analytically-defined facets of intelligence, as proposed by Carroll (1993).

Despite limited existing research, evidence arises from several studies suggesting that math achievement reflects at least two intertwined neuropsychological abilities (spatial and executive functions) independent of general intelligence (Geary, 1993; Rourke, 1993). For example, Assel, Landry, Swank, Smith and Steelman (2003) used a unique approach to demonstrate executive function and visuospatial relationships with math achievement and to provide evidence of a developmental trajectory for math achievement. Rather than using a traditional executive function test, a goal-directed play measure that improves during middle childhood in tandem with improvement in executive functioning and correlates with Tower of London performance was utilized. Using structural equation modeling, Assel and colleagues (2003) showed that visuospatial ability related to later executive function but not vice versa, pointing to a developmental trajectory in which spatial skills develop prior to and underlie executive functions but in which both cognitive abilities have separate specific effects on math skills.

Other studies also support the existence of spatial and executive function components in math achievement, although this support is evident only after a critical examination of the tests that were utilized. For example, although Floyd and associates (2003) found fluid intelligence (Gf) to be related to math achievement when using a Cattell-Horn-Carroll approach, he did not find evidence for visual (Gv)/ math relationships. However, the WJ-R visual factor (Gv) emphasizes aspects of visual perceptual processing (e.g., closure speed, visual memory) to a greater extent than spatial ability, making the Gv factor perhaps less sensitive to the type of visual abilities (i.e., spatial visualization and spatial relations) important in math skill development (Geary, Hamson, & Hoard, 2000; McGrew, Flanagan, Keith, & Vanderwood, 1997). In support of this interpretation, others using purer measures of visuospatial ability (e.g., WAIS Block Design: Batchelor, Gray, & Dean, 1990; Standford-Binet IV Pattern Analysis and Copying: Assel et al., 2003; Benton Judgment of Line Orientation: Riccio & Hynd, 1992) have found a relationship between visuospatial ability and math skill.

Given the Assell et al. (2003) results (that spatial skills develop prior to and underlie executive functions but that both abilities have separate specific effects on math skills) it may be expected that individuals with math disability would display spatial or executive function deficits independent of one another. Similar findings have been found in dyslexia and are reflected in the Double Deficit hypothesis (Wolf & Bowers, 1999), which also proposes a trajectory for the development of cognitive skills. For example, Wolf (1999) presented results of a cluster analysis showing that a group of problem readers with a single deficit in orthographic skill performed as poorly on several aspects of reading as a group of problem readers with a single deficit in phonologic skill. In all, Wolf found three impaired groups of readers: one with dual deficits in orthographic and phonologic skills that was the most reading-impaired group and two single deficit groups with either orthographic or phonologic deficits. The findings of Assell et al. (2003), Wolf (1999), and Wolf & Bowers (1999) converge to suggest that three groups of math disability might also exist: 1) single spatial deficit group, 2) single executive function deficit group, and 3) a dual deficit spatial and executive function deficit group.

In contrast to the conceptualization that spatial and executive functions underlie math ability, some researchers have identified verbal conceptual/crystallized intelligence (WJ-R Gc) as important to math skill development by virtue of the relationship between semantic processes and factual mathematical knowledge (Batchelor, Gray, & Dean, 1990; Floyd, Evans, & McGrew, 2003; Geary, 1993). However, Keith (1997) found that "g" ("general intelligence") was strongly related to math achievement, raising the possibility that the relationship of Gc to math skill may be confounded with general intelligence and may not reflect a specific cognitive ability underlying math skill development. Although some evidence exists that Gc contributes unique variance to math skill above and beyond "g" (McGrew, Flanagan, Keith, & Vanderwood, 1997), this finding has not been evaluated in adults.

In addition to verbal/crystallized relationships, some researchers have suggested math skills are associated with different types of memory abilities (working memory, short-term, and long-term). Specifically, Keeler and Swanson (2001) found that both verbal and visuospatial working memory ability in children are related to math skills via an influence upon strategy knowledge for solving math problems. Likewise, Floyd, Evans, and McGrew (2003) found that both short-term (WJ-R Gsm) and long-term retrieval (WJR-Glr) factors of intelligence predict math skills throughout childhood and adolescence. In addition, Cirino, Morris, & Morris (2002) found that semantic retrieval significantly contributed to math disability in a group of college students referred for a learning disability evaluation.

Overall, a review of the existing literature provides rationale to investigate a number of cognitive components that may contribute to math ability, including spatial and executive functions, crystallized intelligence, and various types of memory (working memory, short-term, and long-term). These findings, issuing largely from work in children, have been largely mirrored in the limited empirical findings from adults (Greiffenstein & Baker, 2002; Katz, Goldstein, & Beers, 2001; Morris & Walter, 1991; Rourke & Conway 1997; and McCue, Goldstein, Shelly, & Katz, 1986). The WJ-R was chosen to measure the processing abilities underlying math achievement because it comprehensively surveys the seven factor analytically-defined facets of intelligence (McGrew, 1994). In addition, the WJ-R battery allows measures of underlying cognitive processing disorders to be evaluated in comparison to co-normed math achievement measures. Math achievement measures include WJ-R subtests (Calculation, Applied Problems), which comprise the Broad Math composite score (BM).

Because the WJ-R is weak in providing pure measures of spatial and executive functions, appropriate neuropsychological measures were added, including the Benton Judgment of Line Orientation (JLO; Benton, Hamsher, Varney, & Spreen, 1983) and the Category Test (CT; Reitan & Wolfson, 1993). The JLO was chosen because of its demonstrated ability to measure spatial perceptual abilities, independent of other cognitive abilities including executive functions (Ng et al., 2000). The CT was chosen because of its accepted relationship to executive function (Perrine, 1993) and because of its demonstrated relationship to math ability on both the WAIS-R and WRAT (Golden, Kushner, Lee, & McMorrow, 1998; Strang & Rourke, 1983). Since, as mentioned previously (Assel et al. 2003), spatial abilities may underlie executive functions in adults, no attempt was made to choose an executive measure that was free of spatial ability.

The current study attempted to evaluate processing disorders that underlie math achievement and dyscalculia in college-age adults. The following hypotheses were made:

1. Based upon the past empirical relationship of spatial ability and math skill, it was predicted that the WJ-R visual processing factor (Gv) and the JLO would differentiate those with poor math skills from those with good math skills.
2. Based upon the past empirical relationship of verbal ability and math skill, it was predicted that the WJ-R auditory processing factor (Ga, as a measure of auditory processing

underlying verbal ability) and crystallized intelligence (Gc) would differentiate those with poor math skills from those with good math skills.
3. Based upon the past empirical relationship of executive ability and math skill, it was predicted that the WJ-R fluid intelligence factor (Gf) and the CT would differentiate those with poor math skills from those with good math skills.
4. Based upon the accepted relationship of memory ability and math skill, it was predicted that the WJ-R memory factors (Glr and Gsm) would differentiate those with poor math skills from those with good math skills.
5. Consistent with the preceding predictions, spatial and executive function processes were expected to predict unique variance in math skill above and beyond the contribution of general intelligence. However, absent precedent literature, specific predictor variables were not able to be identified.
6. Finally, it was predicted that three prototypical subtypes of dyscalculia would be identified, including one subtype with a specific spatial deficit, one with a specific executive function deficit, and one with dual spatial and executive function deficits.

Method

Participants

Participants were 138 (63 males and 75 females) students at an urban university consecutively referred for an assessment of learning disability (LD) and are essentially identical to the archived data presented in Osmon, Braun, Plambeck (2005). Ages ranged from 18–54 years (M = 27.57; SD = 9.78), and because all were currently enrolled in college, education ranged from 12–18 years (M = 14.17; SD = 1..63). The sample was about 92% Caucasian, 8% African-American, and <1% other races. Exclusionary criteria consisted of a diagnosis of psychosis or a neurological condition including traumatic brain injury for which hospitalization occurred. All participants were treated in accordance with university regulations regarding human research subjects.

Summary measures of intelligence revealed a mean Broad Cognitive Ability-Standard (BCA-Std) score of 97 (SD = 11), a mean Broad Math (BM) score of 96 (SD = 17), a mean Calculation score of 95 (SD = 18), and a mean Applied Problems score of 91 (SD = 20), consistent with a sample having learning difficulty. For purposes of comparison, participants were divided into math-impaired (BM standard score ≤84) and math-unimpaired subjects (BM standard score >84), consistent with past practices in defining learning disability (e.g., Keeler & Swanson, 2001). Forty-five participants comprised the dyscalculia group (32% of total sample), with math-unimpaired participants comprising the remainder of the sample. Males made up 36% (N = 16) of the dyscalculia group, whereas the math-unimpaired group was 48% male (N = 45) (no cells were significant by Chi-Square in a group by sex analysis). Age did not differ between math-impaired and math-unimpaired participants (t[138] = 1.25, p>.21) but education did differ significantly between groups (t[138] = 2.21, p<.05) with the unimpaired group being slightly less educated (13.94 vs. 14.67 years).

Procedure

All participants underwent a broad-based neuropsychological evaluation consisting of approximately seven hours of testing over two sessions. The examiner was not aware of hypotheses because data were archival. Tasks were administered in a fixed order.

Measures

Woodcock Johnson-Revised. The WJ-R was designed to evaluate a wide range of neuropsychologically-relevant abilities, based on the Cattell-Horn-Carroll theory of intelligence (Flanagan, Genshaft, & Harrison, 1997). Participants completed all standard and supplemental Tests of Cognitive Ability except Sound Patterns, Spatial Relations, and Verbal Analogies. The following tasks were used in the present analysis:

1. Memory for Names and Visual-Auditory Learning (verbal/nonverbal learning, Glr),
2. Memory for Sentences and Memory for Words (verbal span, Gsm),
3. Visual Matching and Cross Out (rapid visual digit matching and scanning, Gs),
4. Incomplete Words and Sound Blending (auditory processing and synthesis, Ga),
5. Visual Closure and Picture Recognition (visual processing and synthesis, Gv),
6. Picture Vocabulary and Oral Vocabulary (comprehension-knowledge, Gc), and
7. Analysis-Synthesis and Concept Formation (fluid reasoning of visual information, Gf).

The BCAStd is a cluster score derived from these seven standard subtests, and represents a general measure of intellectual ability. In addition, participants completed the WJ-R Achievement battery, including the two math subtests (Calculation and Applied Problems) that make up the BM composite score. These included Calculation, which requires completion of written math problems and Applied Problems, which requires solutions to word problems. To insure accuracy test performance was scored using the test publisher’s computer program according to age norms.

Benton Judgment of Line Orientation. The JLO measures spatial processing and was administered according to accepted practices (Benton, Hamsher, Varney, Spreen, 1983). Raw scores were both age- and gender-corrected.

Category Test. The CT measures abstract concept formation, use of verbal feedback, maintenance of a current rule/mental set, and visuospatial ability and was administered in accepted fashion. Total raw error scores were age, sex, and education corrected (Heaton, Grant, Matthews, 1991).

Results

To explore the relationship of math achievement to intellectual and neuropsychological performance, a MANOVA followed by oneway ANOVAs (math impaired vs. math unimpaired) were conducted using the intellectual and neuropsychological measures. The MANOVA was significant (Wilks’$[10,128] = 4.29$, $p<.0001$). Main effects were evident for Glr ($F[1, 137] = 11.17$, $p<.002$), Ga ($F[1, 137] = 6.32$, $p<.02$), Gv ($F[1, 137] = 3.97$, $p<.05$), Gc ($F[1, 137] = 15.76$, $p<.0002$), Gf ($F[1, 137] = 21.16$, $p<.0001$), BCAStd ($F[1, 137] = 11.05$, $p<.002$), JLO ($F[1, 137] = 15.84$, $p<.0001$), and CT ($F[1, 137] = 19.15$, $p<.0001$). Table 1 shows the mean scores and standard deviations by group for variables used in the analyses.

Table 2 shows that the correlations between the intellectual factors are generally .3–.5, and that the BM composite correlates around .4–.5 with Glr, Gf, CT, and JLO. Because intellectual and neuropsychological factors were correlated and because past findings do not exist to suggest an order of entry for predictor variables, stepwise multiple regression was used to determine which factors predicted unique variance in math achievement. In

Table 1
Means and Standard Deviations of Woodcock Johnson-Revised and Neuropsychological Variables by Group

	Non-math Impaired		Math-impaired	
Variable	Mean	SD	Mean	SD
Glr	101.50	11.63	94.90	11.19
Gsm	96.64	12.75	91.30	9.37
Gs	99.06	13.33	96.33	12.50
Ga	100.35	11.50	95.50	9.92
Gv	106.40	12.86	101.13	10.36
Gc	101.78	11.37	93.73	10.73
Gf	106.91	11.98	97.23	10.00
BCAStd	99.02	10.45	92.53	8.96
Broad Math	96.58	9.62	75.08	8.20
JLO	104.21	15.53	93.08	16.27
CT	115.01	18.03	103.08	17.21

Glr = Long-term retrieval, Gsm = Short-term memory, Gs = Processing speed, Ga = Auditory processing, Gv = Visual processing, Gc = Crystallized intelligence, Gf = Fluid intelligence, BCAStd = Broad cognitive ability-standard, JLO = Judgment of Line Orientation, CT = Category Test.

order to measure unique specific variance BCAStd was forced into the regressions to take out general intellectual variance. A total of 32.6% of the variance in BM was predicted by all predictors contributing unique variance, including BCAStd ($F[1, 137] = 26.71$, $p<.0001$, adj$R^2 = .157$), Gf ($F[2, 136] = 24.53$, $p<.0001$, change in adj$R^2 = .097$), JLO ($F[3, 135] = 21.47$, $p<.0001$, change in adj$R^2 = .054$), and CT ($F[4, 134] = 17.71$, $p<.0001$, change in adj$R^2 = .018$).

To determine whether different profiles of math ability were evident in the sample, a hierarchical complete linkage cluster analysis was conducted using variables suggested by the above analyses, including BM, BCAStd, Gf, JLO, and CT. The optimal solution was five clusters with the score profiles evident in Table 3. Cluster 1 (N = 14) had mildly low scores (86, 88) on BM and CT with average BCAStd and Gf (98, 94) but above average JLO (115) scores. Likewise, cluster 5 (N = 48) had a mildly low score (85) on BM with average BCAStd and Gf (93, 98) but an above average CT score (111) and a mildly low JLO score (89). Additionally, Cluster 2 (N = 12) had moderately low scores (77) on BM and mild impairment on all other scores (81–89). The other two clusters (3 and 4) both had average BM scores (95, 99) and represented average (N = 36) and above average (N = 30) groups.

Discussion

Results were largely consistent with hypotheses, demonstrating the expected processing abilities underlying math achievement. Specifically, both spatial and executive function abilities were found to relate to math achievement after general intellectual variance was removed. While past studies have found verbal ability to relate strongly to math skills (e.g., Floyd, Evans, & McGrew, 2003), present results suggested that verbal conceptual ability (WJ-R Gc) does not contribute unique variance to explaining math skill, at least in

Table 2
Correlations between Variables used in the Analyses

	WJ-R Glr	WJ-R Gsm	WJ-R Gs	WJ-R Ga	WJ-R Gv	WJ-R Gc	WJ-R Gf	BCA Std	CAT	Mathematics	JLO
WJ-R Glr	1.000	.416	.193	.420	.350	.457	.478	.671	.227	.392	.371
WJ-R Gsm	.416	1.000	.179	.507	.129	.407	.307	.616	–.028	.245	.202
WJ-R Gs	.193	.179	1.000	.143	.176	.121	.294	.482	.115	.107	.080
WJ-R Ga	.420	.507	.143	1.000	.190	.562	.217	.535	.085	.252	.260
WJ-R Gv	.350	.129	.176	.190	1.000	.263	.452	.494	.237	.237	.238
WJ-R Gc	.457	.407	.121	.562	.263	1.000	.367	.696	.187	.337	.303
WJ-R Gf	.478	.307	.294	.217	.452	.367	1.000	.629	.437	.502	.371
BCA Std	.671	.616	.482	.535	.494	.696	.629	1.000	.176	.404	.379
CAT	.227	–.028	.115	.085	.237	.187	.437	.176	1.000	.377	.287
Mathematics	.392	.245	.107	.252	.237	.337	.502	.404	.377	1.000	.426
JLO	.371	.202	.080	.260	.238	.303	.371	.379	.287	.426	1.000

WJ-R = Woodcock-Johnson Revised, Glr = long-term memory, Gsm = short-term memory, Gs = processing speed, Gv = visual processing, Ga = auditory processing, Gc = crystallized intelligence, Gf = fluid intelligence, BCA Std = Broad Cognitive Ability Standard, CAT = Category Test, Mathematics = WJ-R Broad Math, JLO = Benton Judgment of Line Orientation.

Table 3
Mean Standard Score Profile Results from the Cluster Analysis with Standard Deviations

Cluster (N)	BM Mean (SD)	BCA Mean (SD)	Gf Mean(SD)	JLO Mean (SD)	CT Mean (SD)
1 (14)	86(8)	98(5)	94(5)	115(9)	88(12)
2 (12)	77(12)	81(5)	89(7)	86(13)	83(12)
3 (36)	95(10)	97(10)	109(8)	107(13)	128(9)
4 (30)	99(16)	111(8)	118(9)	112(11)	116(13)
5 (48)	85(10)	93(6)	98(7)	89(13)	111(13)

BM = WJ-R Broad Math, BCA = WJ-R Broad Cognitive Ability, Gf = WJ-R Fluid Intelligence, JLO = Benton Judgment of Line Orientation, CT = Category Test.

the present adult LD sample. That is, while Gc differentiated those with and without math difficulty in the present study, regression results suggested that verbal ability contributes to math skill only via general intellectual functioning. Likewise, while memory abilities (i.e., WJ-R Glr and Gsm) differentiated math-impaired and math unimpaired individuals, memory processes did not explain math achievement beyond the contribution of general intelligence.

Thus, specific unique variance in spatial (JLO) and problem-solving (WJ-R Gf and CT) abilities is important in using math skills in adults and are likely important in developing math skill since these same processing disorders have been found in children with math disability (Assel et al., 2003; Geary, 1993). While the present results do not specifically test what aspects of spatial and problem-solving abilities are important in math skills, analysis of the present results does suggest some possibilities for understanding the processing abilities underlying math skills, according to modern factor analysis literature from the Cattell-Horn-Carroll model of cognitive functions. For example, it is instructive to examine spatial functioning by comparing differences between the WJ-R Gv factor and the JLO. While Gv taps into closure speed (WJ-R Visual Closure) and visual memory (WJ-R Picture Recognition) the JLO taps more into visualization and spatial relations (McGrew et al., 1997), especially where executive functions contribute minimally (Ng et al., 2000). Since JLO but not Gv predicts math skill, it would seem that spatial perception is more important to math achievement than general visual processing. This interpretation is consistent with past studies that have shown such spatial tasks as Pattern Analysis from the Stanford-Binet IV and WISC-R Block Design to be related to math skills (Assel et al., 2003; Batchelor, Gray, & Dean, 1990).

The identification of specific problem-solving abilities involved in math skill is more difficult to discern since knowledge of fractionated aspects of this cognitive function is less certain. However, CT contributed unique explanatory variance above and beyond Gf, allowing some comparison of problem-solving abilities that may be important in math achievement. For example, CT differs from both Gf subtests (WJ-R Concept Formation and Analysis-Synthesis) in that the rules for solving the problems on CT are not explained, whereas the rules in Gf subtests are explained and must simply be applied by the examinee. In addition, the CT requires the subject to generate rules and then engage in hypothesis testing to determine whether the rules fit the constraints of the problem according to feedback received. Thus, the executive processes on CT require a generativity and flexibility that is not present on the Gf subtests. So, in addition to general intellectual ability and rule application (Gf), it would appear that rule generation and hypothesis testing are important executive abilities for developing math skill.

However, since the present results are exploratory, further confirmatory analyses are needed to verify these assertions. Such confirmation is especially needed in light of other findings in math disability. Specifically, Bull & Scerif (2001) found a different set of executive/problem-solving abilities correlating with children's math ability. They found that the Wisconsin Card Sorting Task (WCST), Stroop task, and counting span each predicted unique variance in math ability. These measures require different sets of executive abilities, including attribute identification (WCST: Perrine, 1993), mental set inhibition/ flexibility (Stroop: Osmon, 1999), and working memory. While children's and adult's executive contributions to math ability may be different, further work in this area will be needed to determine the processing disorder(s) that underlie math ability.

In addition to demonstrating important processing abilities, present results speak to prototypical subtypes of math difficulty. Present findings are consistent with three subtypes of math learning disability and parallel findings in the reading disability literature that support the Double Deficit hypothesis (Wolf & Bowers, 1999). That is, present results found selective and single deficits in two different processing abilities underlying math skill, echoing findings in the reading literature that showed poor readers had specific deficits in either phonologic or orthographic processes (Wolf, 1999). Current results found evidence for a math disability group with a selective spatial deficit, a group with a selective executive function deficit, and a dual deficit group with impairment in both spatial and executive functions.

Further paralleling the reading literature, the dual deficit math group, like the dual deficit reading group, was associated with both the worst achievement skill development and generally lower scores across all cognitive abilities. Thus, the present results, like the Double Deficit hypothesis in reading, support the idea that fractionated processing disorders underlie learning difficulty. This evidence for specific and separate processing disorders is also consistent with the growing neuropathology literature showing focal congenital lesions (e.g., ectopias: Galaburda, 1994) in learning disability. That is, it is possible that focal and circumscribed lesions are responsible for the selective and specific spatial and executive processing disorders underlying math learning disability. Future studies are needed to pursue this supposition.

Limitations of the present study include the determination of math problems based on cut-off test scores (versus a clinical diagnosis of dyscalculia), and the use of a small sample of math-impaired subjects that may not be representative. Since participants in this study were college students, they may represent a group of learning disabled individuals with somewhat better aptitude and achievement than the greater population of learning disabled individuals. Therefore, this sample may overrepresent math ability in adult developmental dyscalculiacs and could conceivably underestimate the verbal-conceptual and memory contributions to math disability. Future studies should include a larger, more representative sample in order to verify the dual deficit nature of math learning disability in the greater learning disabled population. Additionally, larger samples would allow better control for comorbidity between learning disabilities, something lacking in the present study.

In addition to the previous suggestions, future studies should also replicate these results in children in both cross-sectional and longitudinal studies in order to explore the independence of the two deficits. Some evidence suggests that spatial ability precedes and is crucial to the development of executive/problem-solving functions (Assel et al., 2003), and the relationship of this developmental pattern needs to be replicated and examined for its relevance to the development of math skill. Present results should also be replicated with different spatial and executive/problem-solving functions measures to ensure that the processing disorders found in the current study are truly representative of spatial and executive function domains. Such replication would also be important to further test whether spatial/visualization and problem-solving and flexibility aspects of executive functions are the operative processing abilities in math skill development. Because of the limited range of visuospatial and executive functioning tasks included in the present study, future studies should examine other aspects of these domains that are related to math disability. For example, Geary (1993) suggested an "executive-procedural" deficit typified by deficits in procedural knowledge. Additionally, given the descriptive nature of cluster analysis, replication of the clusters is important in both a similar sample and a broader sample that generalizes beyond college students with learning disability.

Finally, present results suggest that math disability may be associated with altered right hemisphere function that is responsible for the spatial and perhaps even executive/problem-solving function deficits. Therefore, functional neuroimaging studies are needed to evaluate for anomalous lateralization of math skills. Based upon findings in dyslexics showing reduced left hemisphere activation (Pugh et al., 2001), functional neuroimaging studies might be expected to show reduced right hemisphere activation in math-impaired subjects. Also, if the right hemisphere overactivation in poor readers suggesting anomalous brain organization (Pugh et al., 2001) is analogous, left hemisphere overactivation in math-impaired subjects might be expected.

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