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Visual-spatial abilities relate to mathematics achievement in children with heavy prenatal alcohol exposure

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Abstract

Objective—The current study examined the relationship between mathematics and attention, working memory, and visual memory in children with heavy prenatal alcohol exposure and controls.

Method—Fifty-six children (29 AE, 27 CON) were administered measures of global mathematics achievement (WRAT-3 Arithmetic & WISC-III Written Arithmetic), attention, (WISC-III Digit Span forward and Spatial Span forward), working memory (WISC-III Digit Span backward and Spatial Span backward), and visual memory (CANTAB Spatial Recognition Memory and Pattern Recognition Memory). The contribution of cognitive domains to mathematics achievement was analyzed using linear regression techniques. Attention, working memory and visual memory data were entered together on step 1 followed by group on step 2, and the interaction terms on step 3.

Results—Model 1 accounted for a significant amount of variance in both mathematics achievement measures, however, model fit improved with the addition of group on step 2. Significant predictors of mathematics achievement were Spatial Span forward and backward and Spatial Recognition Memory.

Conclusions—These findings suggest that deficits in spatial processing may be related to math impairments seen in FASD. In addition, prenatal alcohol exposure was associated with deficits in mathematics achievement, above and beyond the contribution of general cognitive abilities.

Keywords

Fetal alcohol spectrum disorders (FASD); Fetal alcohol syndrome (FAS); Alcohol related neurodevelopmental disorder (ARND); Learning disorders; Cognition

Introduction

Children with fetal alcohol spectrum disorders (FASD) are at risk for a wide range of difficulties including cognitive, behavioral, and academic deficits. Mathematics has emerged as a particular area of weakness in FASD (Goldschmidt, Richardson, Stoffer, Geva, & Day,

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1996; Howell, Lynch, Platzman, Smith, & Coles, 2006; Jacobson, Dodge, Burden, Klorman, & Jacobson, 2011; Streissguth et al., 1994; Streissguth, Barr, & Sampson, 1990), but only recently have research efforts begun to examine the cognitive mechanisms underlying these impairments. Early investigations focused primarily on gross measures of academic achievement and demonstrated that children with histories of prenatal alcohol exposure perform lower than their typically developing peers (Streissguth et al., 1994; Streissguth et al., 1990) and these effects persist even after controlling for global intellectual functioning (Goldschmidt et al., 1996; Howell et al., 2006).

Neuroimaging studies support these neuropsychological data and suggest that children with prenatal alcohol exposure show abnormalities in brain regions thought to be important for mathematics, particularly parietal areas (Dehaene, Piazza, Pinel, & Cohen, 2003). Parietal regions have been implicated in mathematical function across a wide range of populations, including typically developing children (Cantlon et al., 2011; Davis et al., 2009; Rosenberg-Lee, Barth, & Menon, 2011) and children with developmental disorders (Kesler, Menon, & Reiss, 2006; Lebel, Rasmussen, Wyper, Andrew, & Beaulieu, 2010; Meintjes et al., 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007; Santhanam, Li, Hu, Lynch, & Coles, 2009). Children with FASD have been reported to have thicker cortices (Sowell et al., 2008) and smaller volumes (Archibald et al., 2001) in parietal regions relative to controls, and these abnormalities may be related to their decreased mathematics abilities demonstrated in school and on neuropsychological testing (Riikonen, Salonen, Partanen, & Verho, 1999). In a study that specifically evaluated the relationship between mathematical skill and brain white matter structure using diffusion tensor imaging (DTI) in children with FASD, authors identified four key regions related to mathematical ability (Lebel et al., 2010). These regions were located in left parietal areas, left cerebellum, and bilateral brainstem, highlighting the importance of parietal regions for mathematics functioning and suggest the possibility that other areas may be specific to mathematics in children with FASD.

In addition to structural differences, alterations in brain function related to prenatal alcohol exposure have been noted. One investigation utilized functional magnetic resonance imaging (fMRI) to examine the effects of alcohol exposure on brain activation during a subtraction task (Santhanam et al., 2009). Authors noted decreased neuronal activation in children with FASD in left superior parietal regions, right inferior parietal regions, and medial frontal gyrus. Another fMRI study (Meintjes et al., 2010) demonstrated that while control children activated expected frontal and parietal regions to perform exact addition and number processing tasks, alcohol-exposed children recruited a broader range of parietal regions to complete the same tasks. These effects persisted even after statistically controlling for IQ and further confirm that the parietal lobe is particularly affected by alcohol exposure and may be subsequently related to deficits in mathematical function in children with FASD.

While the majority of literature to date has focused on more global aspects of math functioning, a few studies have sought to evaluate more specific processes underlying mathematics in FASD. Kopera-Frye, Dehaene, and Streissguth (1996) administered a numerical processing battery to adolescents and adults with FASD and controls. Measures included number reading and writing, exact and approximate calculations for addition, subtraction, multiplication, proximity judgment, and cognitive estimation. While alcohol-

exposed subjects performed worse than controls on almost all tasks, the cognitive estimation task had the highest number of subjects with impaired performance (Kopera-Frye, Dehaene, & Streissguth, 1996). Similarly, Jacobson and colleagues (2011) demonstrated that children with FASD were impaired on both exact and approximate calculation skills, number comparison, and proximity judgment. Another recent study examined working memory processes and mathematics performance in children with FASD and controls (Rasmussen & Bisanz, 2011). Authors found that math performance was correlated with 5 of the 6 working memory variables they selected. They also performed an analysis that demonstrated that group differences in math performance were reduced with the addition of three of the working memory measures as covariates, suggesting at least some contribution of these measures to mathematics in their sample. However, the three particular measures selected for this analysis appear to be more related to immediate memory and attention rather than working memory ability specifically.

With respect to models of mathematics deficits, there are generally two competing theories. The first, domain-specific view, suggests that mathematics deficits are related to abnormalities in fundamental numerical processing skills, such as representing numerosity and implicit understanding of exact quantities and approximate magnitudes (Butterworth, 2005). The second, domain-general view, focuses on the contribution of higher order cognitive processes to the development of mathematical ability (Geary, 1993, 2004). However, several researchers suggest that multiple pathways to mathematics difficulties can exist (Dennis, Berch, & Mazzocco, 2009; Fuchs et al., 2010; Rubinsten & Henik, 2009; Spelke & Kinzler, 2007) and the studies of children with FASD to date suggest that both models may provide important information regarding mathematics abilities in this population. The current study utilized the latter position and sought to evaluate several aspects of neuropsychological function that might underlie mathematics achievement in children with FASD.

The domain-general view suggests that mathematical skills are built from other general cognitive systems such as attention (Lindsay, Tomazic, Levine, & Accardo, 1999), working memory (McLean & Hitch, 1999; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Rotzer et al., 2009; Zheng, Swanson, & Marcoulides, 2011), and visual memory (Floyd, Evans, & McGrew, 2003; Passolunghi, Mammarella, & Altoe, 2008), and research within this framework focuses primarily on the relationship between mathematics achievement and these diverse neuropsychological mechanisms. Children with FASD demonstrate impairments in a wide range of cognitive domains, including attention (Coles, Platzman, Lynch, & Freides, 2002; Connor, Streissguth, Sampson, Bookstein, & Barr, 1999; Mattson, Calarco, & Lang, 2006), working memory (Burden, Jacobson, Sokol, & Jacobson, 2005; Green et al., 2009), and visual memory (Aragón et al., 2008; Pei, Rinaldi, Rasmussen, Massey, & Massey, 2008), and it is possible that these deficits contribute to the significant weakness in mathematics abilities also seen in this population. The current study examined the relationship between global measures of mathematics achievement and related measures of attention, working memory, and visual memory function in children with histories of heavy prenatal alcohol exposure and typically developing controls. Previous investigations of FASD that have utilized a domain general approach only focused on the relation between working memory abilities and mathematics (Rasmussen & Bisanz, 2011), thus the current

investigation seeks to build on these findings by investigating the relationship between mathematics and a broader range of cognitive domains. It was hypothesized that alcohol-exposed children would demonstrate impaired mathematics achievement relative to controls and that attention, working memory, and visual memory performance would be significantly associated with children's mathematics function.

Method

General Method

Two groups of children were included in this study: children with histories of heavy prenatal alcohol exposure (the AE group) and typically developing control children (the CON group). All children were recruited as part of a larger ongoing study of the behavioral teratogenicity of alcohol. Both alcohol-exposed and control children are recruited into this larger study via several mechanisms, including professional referral, community outreach, and self-referral. Children in the AE group had histories of heavy prenatal alcohol exposure, defined as maternal consumption of at least 4 drinks per occasion at least once per week or 14 drinks per week on average during pregnancy. Prenatal alcohol exposure history was confirmed retrospectively through multi-source collateral report, including review of available medical, social service, and adoption agency records and maternal report, when available. However, because many children with heavy prenatal alcohol exposure no longer reside with their biological families, precise measures of alcohol consumption were often unavailable. In these cases, mothers were reported to be "alcoholic" or alcohol abusing or dependent during pregnancy. The majority of children in the CON group reside with their biological mothers. Therefore, screening for exposure to alcohol or other teratogens in these children was determined through direct maternal report. Mothers of these children reported little or no (i.e., <1oz AA/day prior to pregnancy recognition) alcohol use during pregnancy. These procedures are in agreement with normative standards for retrospective confirmation of maternal alcohol use within the field of clinical behavioral teratology.

Children in the alcohol-exposed group were evaluated by a dysmorphologist with expertise in alcohol teratogenesis. For the purposes of this research project, FAS diagnoses are based on physical measurements (height or weight <10 percentile), craniofacial structure analysis (presence of at least 2 of the following: short palpebral fissures, smooth philtrum, thin vermillion), evidence of deficient brain growth or abnormal morphogenesis (at least 1 of the following: structural brain abnormalities, head circumference <10th percentile), and alcohol exposure history (Hoyme et al., 2005). 41% of children in the AE group met criteria for FAS.

Children were administered a battery of neuropsychological tests, including measures of general intelligence, language, learning, memory, visual-spatial and visual-motor ability, motor performance, academic performance, and executive function. Specific measures are described below. All test administrators were blind to group status of subjects and test protocols were scored independently by two individuals. The Institutional Review Board approved all procedures.

Subjects

Fifty-six children (29 AE, 27 CON) participated in this study. All children were between the ages of 7 and 12 years. The groups were similar on age, socioeconomic status (SES), sex, race/ethnicity, handedness, and school placement. See Table 1.

Measures

Each child was administered measures of global mathematics achievement and related component processes (attention, working memory, and visual memory) as part of a larger battery of tests, including a Full Scale IQ assessment using the Wechsler Intelligence Scale for Children-Third Edition (WISC-III).

Mathematics Achievement Measures

Wide Range Achievement Test – Third Edition (WRAT-3) Arithmetic Subtest: The arithmetic subtest of the WRAT-3 (Wilkinson, 1993) is a screening measure that assesses basic arithmetic skills, such as verbal counting, addition, subtraction, multiplication, and use of decimals and fractions.

Wechsler Intelligence Scale for Children Third Edition as a Process Instrument (WISC-III PI) Written Arithmetic Subtest: The WISC-III PI (Kaplan, Fein, Kramer, Delis, & Morris, 1999) was developed as a supplement to the Wechsler Intelligence Scale for Children – Third Edition (WISC-III; (Wechsler, 1991) in order to evaluate children's performance from a more process-oriented perspective. The written arithmetic subtest measures basic mathematical skills and also allows for examination of children's mathematical strategy use.

An aggregate measure (MATH z-score) combining both WRAT-3 Arithmetic and WISC-III PI Written Arithmetic z-scores based on normative data was utilized as a single variable assessing mathematics achievement in the current study.

Attention and Working Memory Measures

WISC-III Digit Span: The Digit Span subtest requires children to repeat dictated series of digits forward and backward. Series begin with two digits and continue to increase in length, with two trials at each series length. The forward condition of the Digit Span subtest serves as a measure of auditory attention in the current study while the backward condition was used to assess auditory working memory.

WISC-III PI Spatial Span: The Spatial Span subtest is the nonverbal analogue to the Digit Span subtest. The Spatial Span board consists of 10 cubes arranged in a fixed array. Each block is numbered for the examiner but not the participant. The examiner taps a series of cubes and the subject is required to repeat the sequence of taps. Like the other span subtests, both forward and backward spans are tested and series begin with two cubes and continue to increase in length, with two trials at each series length. The forward condition of the Spatial Span subtest serves as a measure of spatial attention in the current study while the backward condition was used to assess spatial working memory.

Visual Memory Measures

Cambridge Neuropsychological Test Automated Battery (CANTAB) Pattern

Recognition Memory (PRM): The CANTAB (Limited, 2006) is a computerized test battery that reliably assesses cognitive function and underlying neuropsychological mechanisms. In the PRM subtest, subjects are presented with a series of visual patterns one at a time at the center of the screen. Then the subject is presented with pairs of patterns composed of a pattern they have already seen and a novel pattern. The subject must indicate which of the two patterns is one he or she has already seen. The task is then repeated with a series of new patterns.

CANTAB Spatial Recognition Memory (SRM): In the SRM subtest, the subject is presented with a white square, which appears in sequence at five different locations on the screen. Then the subject is presented with pairs of squares, one in a location that the subject has already seen and the other in a novel location. The subject must indicate which square is in a location previously seen. The task is then repeated three more times with a series of new locations.

Statistical Analyses

Demographic Information—Demographic data were analyzed by Chi-square (sex, race/ethnicity, handedness) or standard analysis of variance (ANOVA) techniques (age, FSIQ, and SES as measured by Hollingshead). Significant group differences were followed up with pairwise comparisons (Fisher's least significant difference test). See Table 1.

Mathematics Achievement and Component Processes—To evaluate the role of higher order cognitive abilities in mathematics performance in children with FASD and controls, the contribution of attention, working memory, and visual memory data to general mathematics achievement (an aggregate measure combining both WRAT-3 Arithmetic and WISC-III PI Written Arithmetic z-scores based on normative data) was analyzed using hierarchical linear regression. Attention, working memory, and visual memory data were entered on step 1, followed by group on step 2, and the interaction terms on step 3. An alpha level of $p < .05$ was used to determine statistical significance. The contribution of global intellectual function was also examined by completing a second set of analyses in which FSIQ score was included as an explanatory variable in the model.

Results

Demographic Information

Demographic data are listed in Table 1. Groups were similar on sex [χ^2 (df=1) = 1.08, $p = .299$], race [χ^2 (df=1) = 0.68, $p = .411$], ethnicity [χ^2 (df=1) = 0.68, $p = .411$], handedness [χ^2 (df=1) = 0.33, $p = .566$], grade [F (1, 52) = 0.41, $p = .523$], special education placement [χ^2 (df=1) = 2.40, $p = .121$], SES [F (1, 55) = 0.05, $p = .817$], and age [F (1, 55) = 0.02, $p = .902$]. As anticipated, children in the AE group had significantly lower WISC-III Full Scale IQ (FSIQ) than children in the CON group [F (1,55) = 29.81, $p < .001$] and were more likely to be adopted [χ^2 (df=2) = 38.3, $p < .001$].

Mathematics Achievement and Component Processes

Groups differed significantly (AE < CON) on mathematics achievement ($F(1,55) = 28.92, p < .001$), even when FSIQ was controlled for ($F(1, 53) = 3.91, p = .05$). In addition, groups differed significantly (AE < CON) on all component process measures, with the exception of PRM. Mean mathematics and component process scores for the AE and CON groups are presented in Table 2. Hierarchical multiple regression analyses were conducted to evaluate the effect of group (AE and CON) and attention (digit span forward and spatial span forward), working memory (digit span backward and spatial span backward), and visual memory (SRM and PRM) on mathematics achievement (WISC-III PI and WRAT-3 combined z-score). Zero order correlations among global mathematics achievement, attention, working memory, visual memory, and FSIQ measures are presented in Table 3.

When entered together on step one, attention, working memory, and visual memory accounted for a significant amount of the variance in mathematics achievement ($F(6, 55) = 12.07, R^2 = .596, p < .001$). When coefficients for each measure were evaluated, only spatial span forward ($b = .124, \beta = .287, p = .024$), spatial span backward ($b = .106, \beta = .288, p = .017$), and SRM ($b = .349, \beta = .287, p = .010$) were significant predictors of mathematics achievement. Neither digit span subtests nor PRM were significantly associated with mathematics achievement scores ($p > .10$). Model fit improved with the addition of group on step 2 ($R^2 = .066, p = .004$), however, when entered on step three, the interaction terms did not account for a significant increase in explained variance in mathematics achievement scores ($R^2 = .034, p = .588$). Regression coefficients and achieved power for all dependent variables are listed in Table 4.

Data analyses were repeated with FSIQ included as an explanatory variable. When entered together on step one, attention, working memory, visual memory, and FSIQ accounted for a significant amount of the variance in mathematics achievement scores ($F(7, 55) = 12.70, R^2 = .654, p < .001$). When coefficients for each measure were evaluated, only FSIQ ($b = .035, \beta = .458, p = .007$) and SRM ($b = .330, \beta = .241, p = .023$) were significant predictors of mathematics achievement; spatial span forward ($b = .058, \beta = .133, p = .301$) and spatial span backward ($b = .064, \beta = .173, p = .143$) were no longer significant explanatory variables in the model. In addition, neither digit span subtests nor PRM were significantly associated with WISC-III PI scores ($p > .10$). Model fit improved with the addition of group on step 2 ($R^2 = .031, p = .038$), however, when entered on step three, the interaction terms did not account for a significant increase in explained variance in mathematics achievement scores ($R^2 = .035, p = .535$). Regression coefficients and partial correlations for all dependent variables are listed in Table 5.

Power analyses were conducted using G*Power 3 software (Faul, Erdfelder, Lang, & Buchner, 2007). With observed effect sizes ($R^2 = .596$ to $.654$ and $R^2 = .031$ to $.066$, sample size $n = 56$, and $\alpha = .05$, the study was powered at 95% to yield significant omnibus effects (R^2 deviation from zero) and 25 to 50% to yield significant special effects (R^2 increase).

Discussion

The current study evaluated the relationship between mathematics achievement and attention, working memory, and visual memory ability in children with histories of heavy prenatal alcohol exposure and typically developing controls. Our findings are consistent with the robust literature demonstrating mathematics difficulties in children with FASD (Goldschmidt et al., 1996; Howell et al., 2006; Jacobson et al., 2011; Streissguth et al., 1994; Streissguth et al., 1990) as children in the AE group performed lower on the measure of global mathematics achievement used in this study, even when global intellectual function was accounted for. In addition, our findings suggest that at least some domain-general cognitive abilities are related to mathematics performance in this population.

Across groups, measures of attention, working memory, and visual memory were related to mathematics achievement scores. These findings are consistent with previous studies supporting the domain-general view of mathematics deficits and the importance of intact component neuropsychological processes for proficient math performance in school-aged children (Geary, 1993, 2004). Specifically, spatial span forward and backwards and SRM were significant predictors of mathematics performance in this sample. Thus, it appears that spatial processing may be driving these relationships, rather than actual attention and working memory abilities, *per se*. Several studies have shown that visual-spatial skills support mathematics performance (Bachot, Gevers, Fias, & Roeyers, 2005; Geary, 2004; Mazzocco, Singh Bhatia, & Lesniak-Karpiak, 2006; McCloskey, Caramazza, & Basili, 1985; Vuilleumier, Ortigue, & Brugger, 2004; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006). For example, more basic visual-spatial processing may be important for capabilities such as the proper alignment of digits in arithmetical calculations as well as for understanding the concepts of borrowing and carrying (Venneri, Cornoldi, & Garuti, 2003). In addition, evidence suggests that children represent numerical magnitude on a left-to-right oriented mental number line (Berch, Foley, Hill, & Ryan, 1999; Zorzi et al., 2006). As such, impairments in the ability to visually manipulate information may result in inefficient utilization of this mental representation and subsequently impaired mathematics performance (Bachot et al., 2005; Zorzi et al., 2006). Children with FASD have demonstrated impairments in visual-spatial skills that could be related to their deficits in mathematics achievement (Jirikowic, Carmichael Olson, & Kartin, 2008; Kaemingk & Halverson, 2000; Mattson, Riley, Gramling, Delis, & Jones, 1998; Uecker & Nadel, 1996, 1998). In addition, given the relationship between visual spatial skills and parietal lobe function (Gottlieb & Snyder, 2010), alcohol-exposed children's abnormalities in this brain region (Archibald et al., 2001; Lebel et al., 2010; Meintjes et al., 2010; Santhanam et al., 2009; Sowell et al., 2008) may underlie the relationship between visual spatial functioning and mathematics achievement found in this study.

When FSIQ was included as a variable in the regression model, effects of spatial function on mathematics were attenuated; however, SRM remained a significant explanatory variable in the model. These findings suggest that at least some aspects of spatial processing contribute to mathematics achievement independent of the influence of global intellectual functioning. Spatial span forward and backwards were no longer significantly associated with mathematics achievement once FSIQ scores were taken into account. To the extent that IQ is

comprised, in part, of measures of attention and working memory (forward and backward span), controlling for this variable likely removed important variance of interest resulting in weakened relationships between spatial span tasks and mathematics achievement. The treatment of IQ in studies of developmental disorders is a complex issue, particularly in studies of FASD where low IQ is a hallmark deficit. Setting IQ as a covariate or matching subjects on IQ artificially creates a sample that is not representative of the population under study. Further, it does not necessarily allow causal inference with IQ, particularly when IQ is an intrinsic group feature (Dennis, Francis, et al., 2009). These are important considerations when interpreting the present data. However, our findings do support other studies that have controlled for global intellectual functioning where children with histories of prenatal have shown deficits in mathematics achievement over and above the contribution of IQ (Goldschmidt et al., 1996; Howell et al., 2006). In addition, in one of the few studies of mechanisms of mathematics in FASD, IQ did not mediate the effect of prenatal alcohol exposure on math skills (Jacobson et al., 2011).

Although our data suggest that spatial processing may be the most important predictor of mathematics function in the sample, a large literature has considered how working memory skills support mathematics ability. Children with mathematics learning disabilities consistently demonstrate working memory deficits (McLean & Hitch, 1999) and several investigations have shown that both auditory and spatial working memory measures are strong predictors of mathematics performance (Floyd et al., 2003; Kyttala, Aunio, & Hautamaki, 2010; Meyer et al., 2010; Rosselli, Matute, Pinto, & Ardila, 2006; Zheng et al., 2011). Interestingly, our results did not support a relationship between auditory working memory and mathematics achievement. A few previous studies have demonstrated a similar dissociation between auditory and spatial aspects of working memory, with only spatial measures predicting mathematics achievement (e.g., McLean & Hitch, 1999). However, in the only study to examine working memory and mathematics in FASD, group differences were only found on measures of auditory working memory and spatial aspects of working memory were not correlated with mathematics achievement measures (Rasmussen & Bisanz, 2011). Differences in study design may account for this discrepancy. In the Rasmussen et al. (2011) study, groups were not well matched with regard to demographic variables and some of the measures designated as working memory tasks may be more related to immediate memory and attention. In addition, the choice to evaluate contributory factors using correlations and ANCOVA rather than regression techniques did not allow for direct quantification of the amount of variance accounted for in mathematics achievement by these explanatory variables. Regardless of these fundamental design differences, the inconsistent results between these two studies indicate that the role of working memory as a mechanism of mathematics performance in FASD requires further investigation.

It is possible that non-spatial measures of attention and memory were not related to mathematics in this study due to the use of global measures of mathematics function as the outcome variable, as the measures used in this study primarily target math calculation skills and do not reflect the full range of mathematical thinking and problem-solving skills. It may be that the contribution of varying neuropsychological components differs as a function of mathematical domain. For example, auditory working memory may play a role in verbal counting difficulties in children with mathematics difficulties (Logie & Baddeley, 1987;

Logie, Gilhooly, & Wynn, 1994), whereas impairments in visual-spatial working memory may be responsible for children's errors in mental calculations (Venneri et al., 2003). Future studies should include a more fine-grained analysis of mathematics abilities to better determine whether auditory aspects of attention and working memory are related to mathematics in FASD. It is also possible that auditory aspects of attention and working memory are important for mathematics ability in general, but that children with FASD, in particular, demonstrate unique spatial mechanisms of mathematics performance. Differing profiles of mathematics impairments and related skill difficulty have been able to distinguish other syndrome groups (Murphy & Mazzocco, 2008), thus future studies should compare domain-general abilities in children with FASD to those in other clinical populations to better determine how visual-spatial function is specifically contributing to mathematics in alcohol-exposed individuals.

In addition to demonstrating that domain-general cognitive abilities were related to mathematics achievement in this sample, we also found that the inclusion of group in our model accounted for additional explained variance in mathematics scores. This finding suggests that cognitive abilities do not completely account for mathematics performance in children with FASD, but that other factors related to alcohol-exposure are associated with additional deficits in mathematics scores. These additional explanatory variables might include domain-specific factors related to mathematics (i.e. fundamental numerical processing skills), which have been investigated in two studies of FASD. In fact, in the study by Jacobson et al., the relationship between prenatal alcohol exposure and calculation was fully mediated by magnitude comparison, a basic numerical processing task (Jacobson et al., 2011). This might suggest that a domain-specific model of mathematical ability is the most parsimonious approach for understanding mathematics performance in children with FASD. However, relationships might also depend on the specific type of math problems under investigation. In a study by Fuchs et al. (2010), authors analyzed the interplay between basic numerical processing skills and domain-general abilities in explaining school mathematics learning. They showed that for both procedural calculations and word problems, domain-specific numerical cognition was uniquely predictive of performance. However, for only word problems, a set of domain-general abilities provided additional unique explanatory value. Again, more fine-grained analysis of specific mathematical abilities will be important in addressing this issue and future studies should be more comprehensive, including both domain-general and domain-specific factors together in order to understand the relative importance of these models in explaining mathematics deficits in FASD.

Limitations and Future Directions

As stated previously, our primary outcome variable included gross measures of mathematics function that evaluated one aspect of mathematical problem solving (calculation) although it is possible that varying general cognitive skills may be differentially related to mathematics depending on the type of problem and different relationships could emerge when examining more specific types of mathematical skills. Future studies should include a more detailed analysis of mathematics in order to better understand the complex mechanisms underlying these skills. Similarly, the three domain-general skills assessed in this study (attention,

working memory, and visual memory) also are multifaceted and can be measured in different modalities and using different tasks. Thus, it is possible that distinctive components of these skills are differentially related to mathematics skills. For example, when investigating working memory, the construct is often divided into three parts based on the model by Baddeley and Hitch (1994): the visual-spatial sketchpad, phonological loop, and central executive, and these components have been shown to differentially relate to math performance (Meyer et al., 2010). We attempted to address this, in part, by including both auditory and spatial aspects of neuropsychological domains, however future studies could take an even more comprehensive approach. Also, given the cross sectional and correlational nature of the study, it is unclear if these processes are causal factors for deficits in math in FASD.

In the current study, spatial aspects of attention, working memory, and visual memory appeared to be the most important factors related to mathematics performance. However, because spatial abilities are cognitively complex and were only measured in relation to other skills (i.e. spatial attention, spatial working memory, visual-spatial memory), the specific role of visual-spatial functioning in math could not be determined. Future studies should consider the role of basic visual-spatial processing (e.g., visual scanning, spatial orientation, line bisection) to better understand how it might support mathematics in children with FASD.

Finally, although consistent with other studies of mathematics in children affected by prenatal alcohol exposure, the sample used in this study was relatively small in size, and therefore results must be interpreted cautiously. Replications of these findings are critical to better understand the nature of mathematics functioning in children with FASD.

In summary, this study confirms previous findings of mathematics deficits in children with FASD and is the first to demonstrate that spatial aspects of attention, working memory, and visual memory are related to global mathematics scores in a sample of children with heavy prenatal alcohol exposure. These data also suggest that heavy prenatal alcohol exposure is associated with deficits in mathematics achievement above and beyond the contribution of general cognitive abilities. Mathematics is one of the few domains in which interventions for alcohol-exposed children have been successful (Coles, Kable, & Taddeo, 2009; Kable, Coles, & Taddeo, 2007). Greater understanding of the mechanisms underlying these deficits could strengthen these therapies and have important implications for affected children.

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Table 1

Demographic information for AE and CON groups

Variable	AE	CON
N	29	27
Sex [N (%) Female]	10 (34.50)	13 (48.10)
Race [N (%) White]	18 (62.10)	20 (74.10)
Ethnicity [N (%) Hispanic]	4 (13.80)	6 (22.20)
Handedness [N (%) Right]	23 (79.30)	23 (85.20)
Age in years [M (SD)]	10.02 (1.86)	10.08 (1.77)
School placement		
Grade [M (SD)]	4.3 (1.98)	4.6 (1.77)
Special education classes [N (%)]	8 (27.6)	3 (11.1)
SES [M (SD)]	49.38 (12.97)	48.57 (12.88)
Home environment *		
Biological [N (%)]	4 (13.8)	26 (96.3)
Adopted [N (%)]	24 (82.8)	1 (3.7)
Foster [N (%)]	1 (3.4)	0 (0.0)
FSIQ [M (SD)]*	85.90 (16.31)	108.30 (14.22)
Diagnosis [N (%) FAS]	12 (41.40)	0 (0)

* significant at the $p < .05$ level

Table 2

Mean performance for AE and CON groups on measures of global mathematics achievement, attention, working memory, and visual memory.

Measure	AE	CON
Mathematics Achievement Measure		
WRAT-3 ^a /WISC-III ^b combined score (MATH z-score) [M (SD)] ^{*I}	-1.04 (1.05)	0.65 (1.30)
Component Process Measures		
WISC-III Digit Span Forward [M (SD)] ^{*2}	7.69 (2.33)	10.37 (2.99)
WISC-III Spatial Span Forward [M (SD)] ^{*2}	7.34 (3.02)	10.37 (2.95)
WISC-III Digit Span Backward [M (SD)] ^{*2}	7.62 (3.28)	9.81 (3.63)
WISC-III Spatial Span Backward [M (SD)] ^{*2}	8.07 (4.18)	10.41 (3.27)
PRM ^c [M (SD)] ^I	-0.31 (1.02)	0.05 (0.81)
SRM ^d [M (SD)] ^{*I}	-1.00 (1.00)	-0.35 (1.03)

* significant at the $p < .05$ level

^I Data reported as z-scores

² Data reported as Scaled Scores

^a Wide Range Achievement Test – Third Edition Arithmetic Subtest

^b Wechsler Intelligence Scale for Children Third Edition as a Process Instrument Written Arithmetic Subtest

^c Pattern Recognition Memory from the CANTAB

^d Spatial Recognition Memory from the CANTAB

Table 3

Zero order correlations for measures of global mathematics achievement, attention, working memory, and visual memory.

	MATH z-score ¹	FSIQ	Digit Span Forward	Spatial Span Forward	Digit Span Backward	Spatial Span Backward	PRM ²	SRM ³
MATH z-score ¹	1							
FSIQ	.761**	1						
Digit Span Forward	.425**	.485**	1					
Spatial Span Forward	.618**	.717**	.347**	1				
Digit Span Backward	.485**	.592**	.488**	.425**	1			
Spatial Span Backward	.606**	.646**	.246	.601**	.334*	1		
PRM	.323*	.450**	.106	.357**	.177	.322*	1	
SRM	.527**	.461**	.425**	.271**	.362**	.295*	.330*	1

¹ z-score (aggregate measure of both WRAT-3 Arithmetic and WISC-III PI Written Arithmetic standardized scores)

² Pattern Recognition Memory from the CANTAB

³ Spatial Recognition Memory from the CANTAB

* significant at the p < .05 level

** significant at the p < .01 level

Table 4

Regression coefficients for attention, working memory, and visual memory dependent variables.

Measure	Unstandardized Coefficient (<i>b</i>)	Standardized Coefficient (β)	Partial Correlation	Significance (<i>p</i>)
Digit Span Forward	.034	.070	.089	.534
Spatial Span Forward	.124	.278	.316	.024
Digit Span Backward	.052	.128	.163	.254
Spatial Span Backward	.106	.288	.334	.017
PRM ¹	.005	.003	.004	.977
SRM ²	.394	.287	.356	.010
Group	.887	.310	.403	.004
Digit Span Forward $\times$ Group	.030	.116	.041	.791
Spatial Span Forward $\times$ Group	.072	.278	.104	.500
Digit Span Backward $\times$ Group	.127	.489	.216	.159
Spatial Span Backward $\times$ Group	-.052	-.206	-.091	.556
PRM ¹ $\times$ Group	-.322	-.125	-.151	.327
SRM ² $\times$ Group	-.039	-.019	-.020	.896

¹ Pattern Recognition Memory from the CANTAB

² Spatial Recognition Memory from the CANTAB

Table 5

Regression coefficients for attention, working memory, and visual memory dependent variables, with FSIQ included in the model.

Measure	Unstandardized Coefficient (<i>b</i>)	Standardized Coefficient (β)	Partial Correlation	Significance (<i>p</i>)
FSIQ	.035	.458	.378	.007
Digit Span Forward	.005	.010	.013	.929
Spatial Span Forward	.058	.133	.149	.301
Digit Span Backward	.008	.020	.026	.855
Spatial Span Backward	.064	.173	.210	.143
PRM ¹	-.108	-.070	-.102	.480
SRM ²	.330	.241	.322	.023
Group	.661	.231	.591	.038
Digit Span Forward $\times$ Group	.059	.231	.084	.596
Spatial Span Forward $\times$ Group	.055	.213	.083	.596
Digit Span Backward $\times$ Group	.126	.483	.222	.152
Spatial Span Backward $\times$ Group	-.033	-.132	-.061	.699
PRM ¹ $\times$ Group	-.272	-.105	-.133	.395
SRM ² $\times$ Group	-.036	-.018	-.019	.902

¹ Pattern Recognition Memory from the CANTAB

² Spatial Recognition Memory from the CANTAB