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Individual differences in left parietal white matter predict math scores on the Preliminary Scholastic Aptitude Test

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ABSTRACT

Mathematical skills are of critical importance, both academically and in everyday life. Neuroimaging research has primarily focused on the relationship between mathematical skills and functional brain activity. Comparatively few studies have examined which white matter regions support mathematical abilities. The current study uses diffusion tensor imaging (DTI) to test whether individual differences in white matter predict performance on the math subtest of the Preliminary Scholastic Aptitude Test (PSAT). Grades 10 and 11 PSAT scores were obtained from 30 young adults (ages 17–18) with wide-ranging math achievement levels. Tract based spatial statistics was used to examine the correlation between PSAT math scores, fractional anisotropy (FA), radial diffusivity (RD) and axial diffusivity (AD). FA in left parietal white matter was positively correlated with math PSAT scores (specifically in the left superior longitudinal fasciculus, left superior corona radiata, and left corticospinal tract) after controlling for chronological age and same grade PSAT critical reading scores. Furthermore, RD, but not AD, was correlated with PSAT math scores in these white matter microstructures. The negative correlation with RD further suggests that participants with higher PSAT math scores have greater white matter integrity in this region. Individual differences in FA and RD may reflect variability in experience dependent plasticity over the course of learning and development. These results are the first to demonstrate that individual differences in white matter are associated with mathematical abilities on a nationally administered scholastic aptitude measure.

Introduction

Mathematical skills are of critical importance academically and in everyday life. Functional neuroimaging has provided evidence for the involvement of a fronto-parietal network in numerical and mathematical processing, which includes the intraparietal sulcus, superior parietal lobule, angular gyrus, supra-marginal gyrus, and inferior, middle and superior frontal gyri (Ansari, 2008; Arsalidou and Taylor, 2011; Cohen Kadosh et al., 2008; Dehaene et al., 2003). Traditionally, research on the neural underpinnings of mathematical skills has primarily focused on understanding brain function, and comparatively less is known about underlying brain structure. The present paper reports an investigation of the relationship between individual differences in high-school level mathematical achievement scores and variability in white matter measured by Diffusion Tensor Imaging (DTI).

DTI is an MRI technique that examines white matter microstructure and yields several parameters that can be indicative of white matter integrity and can be used in brain–behavior correlations. Fractional anisotropy (FA) is related to axonal membranes, axonal packing, and myelination (Beaulieu, 2002). Other diffusion parameters such as axial (AD) and radial diffusivity (RD) can further elucidate the sources of anisotropy. A number of studies have used DTI to examine how cognitive processes are related to brain structure. In the literature on the relationship between mathematical cognition and white matter integrity, several different approaches have been used. Specifically, various analytical techniques have been employed (region of interest, tractography and voxel-wise correlations), and diverse populations have been studied (typically and atypically developing). Overall, there is some evidence to suggest that left parietal white matter structures are important for numerical and mathematical processing. For example, van Eimeren et al. (2008) used an anatomical regions of interest approach (ROI) and found a correlation between individual differences in children's (7–9 years) scores on a written calculation test and fractional anisotropy (FA) in the left inferior longitudinal fasciculus and the left superior corona radiata. Using tractography to define regions within which correlations were conducted, Tsang et al. (2009) found that the left anterior superior longitudinal fasciculus was correlated with approximate, but not exact addition in children (10–15 years). In both adults and children, more basic number processing (magnitude comparison) has been related to FA in the left isthmus of the corpus callosum, but not in the

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right (Cantlon et al., 2011). The authors speculated that relatively weak white matter integrity of the left isthmus may be related to more right hemisphere activation in children compared to adults during numerical tasks. They additionally hypothesized that this interhemispheric connection and the increasing involvement of the left hemisphere over the course of development could play an important role in the maturation of numerical representations. In sum, studies on typical development suggest that the specialization of left parietal white matter is important for arithmetic and basic numeracy skills.

Several DTI studies with atypically developing populations (i.e. dyscalculia, fetal alcohol spectrum disorder, multiple sclerosis, and velocardiofacial syndrome) have also demonstrated correlation between mathematical abilities and diffusion parameters (Barnea-Goraly et al., 2005; Lebel et al., 2010; Rykhlevskaia et al., 2009; Till et al., 2011). However, these studies have yielded somewhat more mixed results with some demonstrating correlations in right parietal (Rykhlevskaia et al., 2009; Till et al., 2011) and right frontal microstructures (Till et al., 2011), or the left corticospinal tract, cerebellar pundicle, and bilateral projection fibers (Lebel et al., 2010). Yet, research on velocardiofacial syndrome and fetal alcohol spectrum disorder have uncovered correlations between mathematical skills of individuals with these disorders and left parietal microstructures, which is consistent with the literature on typically developing individuals (Barnea-Goraly et al., 2005; Lebel et al., 2010). Thus, there is some level of consensus in the findings from both typically and atypically developing populations that individual differences in numerical and mathematical skills are related to white matter microstructures in the left parietal lobe.

What is currently unclear is whether the relationship between white matter microstructure and mathematical competence would still hold for more complex, educationally relevant measures. The available studies have used measures of mathematical skills that focus on basic mathematical (such as exact and approximate arithmetic) and number skills (such as number comparison) as opposed to measures of more complex, higher-level mathematical skills (such as algebra).

To address the outstanding question of which white matter structures are related to individual differences in higher-level mathematical skills, the present study examines whether higher level mathematical abilities such as algebra, complex geometry or complex arithmetic are related to variability in left parietal white matter microstructures, such as those highlighted above, or whether higher level mathematical skills are related to an entirely different set of regions. On the one hand, it may be hypothesized that complex mathematical abilities may rely on white matter structures similar to those of more basic mathematical skills (such as single-digit arithmetic or approximate addition). If this is true, it may suggest that later mathematical abilities are scaffolded on earlier mathematical skills. On the other hand, it is equally plausible that more complex mathematical tasks may rely on a different set of regions. With increasing task complexity, a larger number of areas may be needed to subserve aspects of processing that are required for success in the application of higher-level math skills, but play no role in more basic arithmetic and numerical skills.

The above-discussed studies on typical development exclusively examined correlations between mathematical skills and FA. Other measures of white matter that can be derived from DTI data, such as radial diffusivity (RD) and axial diffusivity (AD), have not been considered in research on the relationship between mathematical abilities and white matter in a typically developing population. An examination of other diffusion parameters has been informative in studies on atypically developing populations (Lebel et al., 2010; Rykhlevskaia et al., 2009). For example, Lebel et al. (2010) found two clusters in left parietal regions and a cluster in the left cerebellum that demonstrated a positive correlation between FA and math performance. In addition, clusters in bilateral regions of the brainstem showed a negative correlation between FA and math scores. They further examined radial (perpendicular diffusivity) and axial diffusivity (parallel diffusivity) in each of these regions to determine the primary cause of the correlations with FA. This analysis revealed that axial, but not radial diffusivity, was positively correlated with math scores in the two left parietal clusters, whereas radial, but not axial, diffusivity was negatively correlated with math scores in the other two regions. These results suggest that there may be different underlying contributors to correlations with FA, and examining parameters such as AD an RD may be useful in determining the sources of anisotropy. Thus, investigating these parameters in a typically developing population may provide additional information on the cause of correlation between math scores and FA.

To address these outstanding questions and extend our understanding of the structural neuroanatomy that supports mathematical cognition, the current study uses DTI to examine whether individual differences in white matter integrity (using measures of FA, RD and AD) predict performance on the math subtest of the Preliminary Scholastic Aptitude Test (PSAT), a broad and widely utilized measure used to predict college achievement. To the best of our knowledge this is the first study that has related college-level math achievement scores to individual differences in white matter. The present study has several aims: (1) Determine which white matter structures are associated with broad, complex, and educationally relevant measures of mathematics; (2) Examine whether individual differences in white matter integrity predict mathematical skills above and beyond other measures of scholastic aptitude; and (3) Explore the relationship between mathematical competence and radial as well as axial diffusivity to further elucidate any correlations with FA.

Materials and methods

Participants

Participants were recruited as part of a larger longitudinal study of mathematical development (Mazzocco and Devlin, 2008) from a suburban public school district in the greater Baltimore region of Maryland, USA. When the cohort reached Grade 12, a representative sample of these students was recruited to participate in an MRI study. Thirty young adults between ages 17–18 (M = 18.0; SD = 0.4) years participated in this study (15 female, 30 right handed). Forty-three participants were originally scanned, however only 30 had all behavioral measures. All participants consented to sharing their official College Board test results.

Preliminary Scholastic Aptitude Test (PSAT)

We used the math subtest of the PSAT as a measure of mathematical competence. The PSAT is used to reliably predict college entrance exam scores and is taken by over 3.5 million high school students in the United States every year. This test is also the qualifying exam for the U.S. Merit-based Scholarship Program. Consequently, this measure is highly educationally relevant and has been designed to predict future academic success.

The math subtest of the PSAT contains a wide variety of mathematical problems that range in difficulty; it consists of 38 questions including word problems, geometry, algebraic equations, and complex arithmetic. Importantly, the test, unlike the measures used in previous studies of the association between individual differences in white matter structure and mathematical competence, assesses skills beyond basic arithmetic. The participants in this sample completed the PSAT in Grades 10 and 11. Since DTI data were collected in Grade 12, scores from both grades were used to examine the reliability of correlations with DTI parameters across two different time-points. PSAT subtests have standard scores that range from 20 to 80. The national average for the math subtest was 44.3 (SD = 11.1) in Grades 10 and 48.3 (SD = 11.4) in Grade 11. Our participants demonstrated a wide range of achievement levels on the PSAT math subtest in Grade 10 (M = 49.9, SD = 10.4) and Grade 11 (M = 54.7, SD = 10.6). As anticipated,