NeuroImage 66 (2013) 604–610

Contents lists available at SciVerse ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

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

Anna A. Matejko [a], Gavin R. Price [a], Michèle M.M. Mazzocco [b], Daniel Ansari [a,*]

[a] Numerical Cognition Laboratory, Department of Psychology and Institute for Brain and Mind, The University of Western Ontario, London, ON, Canada
[b] Institute of Child Development and the Center for Early Education and Development, University of Minnesota, Minneapolis MN, USA

ARTICLE INFO

Article history:
Accepted 4 October 2012
Available online 27 October 2012

Keywords:
Diffusion tensor imaging (DTI)
White matter
Fractional anisotropy (FA)
Radial diffusivity (RD)
Tract based spatial statistics (TBSS)
Mathematical cognition

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

* Corresponding author at: Department of Psychology, The University of Western Ontario, Westminster Hall, Room 325, London, ON, Canada N6A 3K7. Fax: +1 519 850 2554.
E-mail addresses: amatejko@uwo.ca (A.A. Matejko), gavinprice@gmail.com (G.R. Price), mazzocco@umn.edu (M.M.M. Mazzocco), daniel.ansari@uwo.ca (D. Ansari).

1053-8119/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.neuroimage.2012.10.045

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, there was a strong correlation between PSAT 10 and 11 math scores, $r(28)=.86$, $p<.001$.

To control for non-mathematical academic competence, scores from the PSAT critical reading subtest were also collected in Grades 10 ($M=47.2$, $SD=9.3$) and 11 ($M=51.8$, $SD=9.5$). The national average for the critical reading subtest was 41.9 (SD = 11.4) in Grade 10 and 47.0 (SD = 11.5) in Grade 11. This subtest includes sentence completion (deciphering the logic of a sentence or understanding the meaning of words in context) and reading comprehension problems (understanding or interpreting written passages). PSAT critical reading and PSAT math subtests were highly correlated in both Grade 10 $r(28)=.50$, $p<.01$ and Grade 11 $r(28)=.49$, $p<.01$.

MRI acquisition and analysis

Participants were scanned on a 3 T Phillips MRI scanner at the FM Kirby Research Center for Functional Brain Imaging in Baltimore, MD, using an 8-channel head coil with parallel imaging capability. Diffusion Tensor Imaging (DTI) data were acquired using a single-shot echo planar imaging sequence (seventy 2.2 mm-thick axial slices with no inter-slice gap, TR = 6995.121 ms, TE = 71 ms, 31 diffusion sensitization gradients (b-value = 700 s/mm^2), a non-diffusion weighted scan, a mean weighted scan (trace), FoV = 212 × 212 × 154 mm, matrix size 96 × 96 reconstructed to 256 × 256, voxel size 2.2 × 2.2 × 2.2 mm reconstructed to 0.83 × 0.83 × 2.2 resulting in an in-plane interpolation). The total DTI acquisition time was 4:05 min.

DTI data were processed using FMRIB Software Library (Smith et al., 2004). We used tract based spatial statistics (TBSS) to compute voxelwise correlations between math PSAT scores, fractional anisotropy (FA), axial diffusivity (AD), and radial diffusivity (RD) (Smith et al., 2006). All data were checked for motion artifacts in all diffusion directions before being included in the TBSS analysis, and none of the 30 participants showed motion related artifacts. After correcting for eddy current distortion effects and using BET to extract the brain, FA was calculated in every voxel by fitting a tensor model to the raw diffusion data. Every subject's FA data were then warped into a common space using the nonlinear registration with FSL. Nonlinear Registration Tool to the standard adult template, FMRIB58_FA. A mean FA image was created and thinned to produce a mean FA skeleton. FA data were then projected onto the skeleton to perform voxelwise statistics. Axial (L1) and Radial (L2 + L3/2) diffusivity maps were also created using FA images for non-linear registration and skeletonization. TBSS analyses were used for radial and axial diffusivity to further constrain the understanding of the nature of any correlations with FA and PSAT math scores. Higher FA could be indicative of increased diffusivity along the primary diffusion axis or it could represent reduced diffusivity along the perpendicular axis.

In the initial TBSS analysis, PSAT Math Scores in Grades 10 and 11 were correlated with FA without any covariates to determine the regions that are correlated with PSAT math without taking into account potential confounding factors. All subsequent analyses used multiple regression statistics to estimate the effects of PSAT math on DTI parameters while controlling for the variance explained by both chronological age and PSAT Critical Reading scores. Therefore, variance from the confound variables was removed from the diffusion parameters (the dependent variables). The addition of these covariates ensures that correlations were specific to mathematics and did not reflect age, higher overall PSAT scores, or general abilities (such as working memory, speed of processing etc.) that may be shared between PSAT critical reading and math subtest and are therefore not specific to math. Numerous studies have demonstrated that diffusion parameters change with age (i.e., Lebel et al., 2008), and given that we had and age range of approximately 1.5 years, we used extra caution by correcting for any variance due to age. Indeed, when we examined whether FA was correlated with age, many voxels were positively correlated ($p<.05$, uncorrected), suggesting that even though a restricted age-range of relatively older participants was used, age was still related to FA, making it an important factor to control for when looking for variability in white matter microstructure specifically associated with mathematics achievement. Thus comparing the correlated regions with and without controlling for PSAT Critical Reading and chronological age allows for an assessment of the effects of these potentially confounding factors.

All reported correlations are corrected for multiple comparisons using Threshold-Free Cluster Enhancement (TFCE). TFCE is similar to cluster-based thresholding except that it does not require an arbitrary definition of the initial cluster-forming threshold (Smith and Nichols, 2009). It is considered to be more robust and provides greater sensitivity than other methods (Smith and Nichols, 2009). All reported results are reported at alpha levels of .05 and also at .01. An alpha level of .01 was reported to determine white matter regions that were most strongly correlated with PSAT math scores.

Results

The first analysis explored which white matter regions were correlated with PSAT Math scores without including any covariates. In this analysis a large number of fronto-parietal regions were positively correlated with PSAT Math scores (TFCE corrected) (Fig. 1). White matter tracts that were positively correlated with Grade 10 scores ($p<.05$) included the bilateral corticospinal tract, superior corona radiata, cingulum, corpus callosum, posterior thalamic radiation, the left inferior fronto-occipital fasciculus, right inferior longitudinal fasciculus, right anterior limb of the internal capsule, right uncinate fasciculus, and the right superior longitudinal fasciculus (the anatomical locations were determined using the JHU ICBM–DTI White Matter Atlas, JHU White Matter Tractography Atlas and the Juelich Histological Atlas). At a higher threshold of $p<.01$, all of these regions remained significantly correlated with math scores. FA and PSAT Math 11 correlations ($p<.05$) closely overlapped those with PSAT Math 10, and included the same tracts listed above as well as the left anterior thalamic radiation. However this additional tract did not survive a threshold of $p<.01$ (Fig. 1)

In order to determine which regions were specifically related to mathematical competence, we carried out a second analysis correcting for age and PSAT Critical Reading. At an alpha level of .05, Grade 10 PSAT math scores positively correlated with FA in several regions: bilateral superior corona radiata, bilateral corticospinal tract, bilateral superior longitudinal fasciculus, corpus callosum, and the left cingulum. Grade 11 PSAT math scores positively correlated with all of the abovementioned regions as well as the bilateral anterior limb of the internal capsule, bilateral anterior corona radiata, bilateral fronto-occipital fasciculus, bilateral uncinate fasciculus, and the right cingulum.

At a higher threshold of $p<.01$, only FA in left parietal white matter significantly correlated with PSAT math scores in Grade 10, and Grade 11 (TFCE corrected) (all correlation coefficients calculated from mean t-scores from each cluster). In other words, participants with higher PSAT math scores showed higher FA in left parietal white matter (see Fig. 2). Voxels in this cluster spanned three tracts including the left superior longitudinal fasciculus, left corticospinal tract, and the left superior corona radiata. The cluster underlies grey matter in the superior parietal lobule and post-central sulcus, and is near the left intraparietal sulcus. As can been seen from Fig. 2, this correlation was consistent across PSAT math scores in Grade 10 and Grade 11 indicating that time between taking the PSAT math test and the acquisition of the DTI data did not play a significant role in the magnitude of the correlation. No negative correlations were found with FA and PSAT math scores.

We further explored correlations between radial (RD) and axial diffusivity (AD) and PSAT math scores to further elucidate the relationship between FA and PSAT math scores. The TBSS analysis with

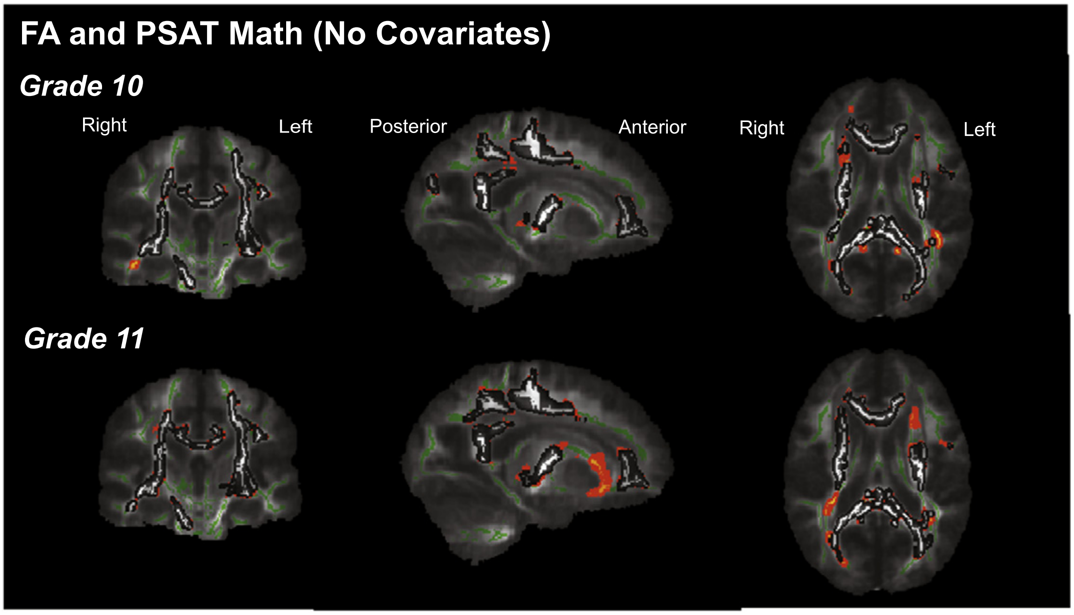

Fig. 1. White matter structures showing a positive correlation between FA and PSAT Math scores in Grade 10 and Grade 11. The red-yellow color gradient represents all regions that are significant where $p<.05$ and the white-black color gradient represents all regions that are significant where $p<.01$. All correlations are TFCE corrected. The statistical map is overlaid onto the mean FA skeleton (green) and the mean FA map of all the subjects. There were no negative correlations between FA and PSAT Math scores.

AD revealed no significant correlation with math scores in either Grade 10 or Grade 11. However, a negative correlation with RD was present in left parietal white matter in both Grade 10 and Grade 11 ($p<.05$) (see Fig. 3). These correlations did not survive .01 thresholds therefore only .05 thresholds are presented. This cluster closely overlaps with the above-mentioned FA and PSAT correlation ($p<.01$). TBSS results with radial diffusivity revealed slightly different patterns for Grades 10 and 11. Correlations with PSAT math scores in Grade 10 show more diffuse correlations including a small cluster in right parietal white matter intersecting the right corticospinal tract, right superior corona radiata, and body of the corpus callosum. Correlations between PSAT math scores in Grade 11 and radial diffusivity were limited to the left parietal region ($p<.05$).

To further explore the specificity of the relationship between left parietal white matter and mathematical scores, simple correlations were conducted between with the diffusion parameters (FA and RD) and PSAT Critical Reading scores in SPSS (Version 20.0). Masks were created based on the above whole brain analyses (with covariates, $p<.01$) and RD (with covariates, $p<.05$). Mean FA and RD values were extracted from each individual's white matter skeleton based on

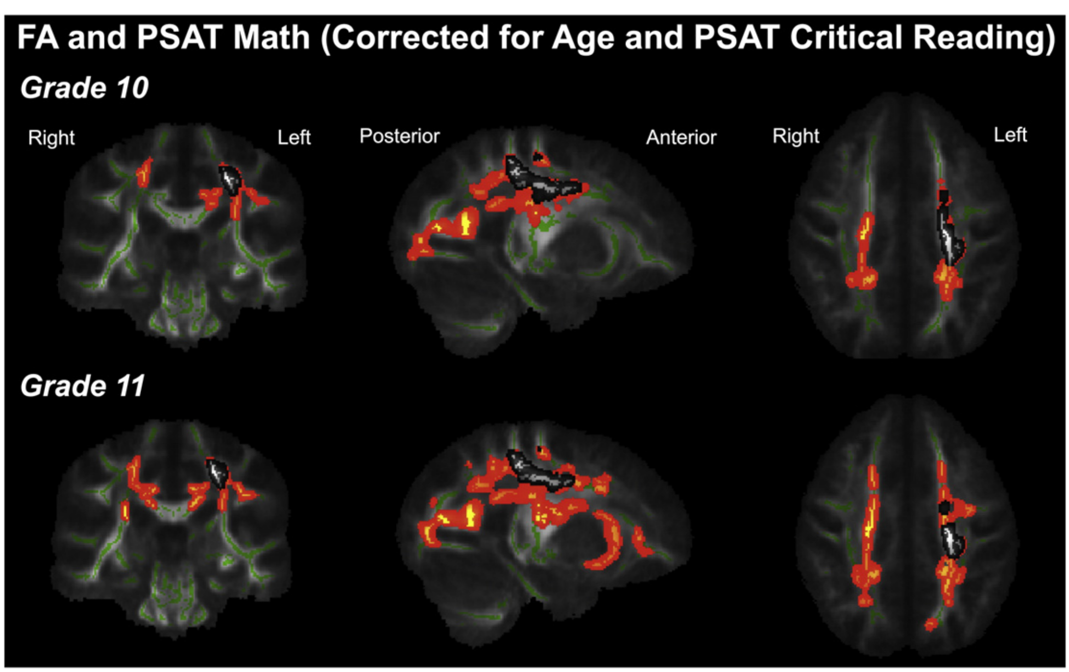

Fig. 2. White matter structures showing a positive correlation between FA and PSAT Math scores in Grade 10 and Grade 11, correcting for chronological age and PSAT Critical Reading scores. The red-yellow color gradient represents all regions that are significant where $p<.05$ and the white-black color gradient represents all regions that are significant where $p<.01$. All correlations are TFCE corrected. The statistical map is overlaid onto the mean FA skeleton (green) and the mean FA map of all the subjects.

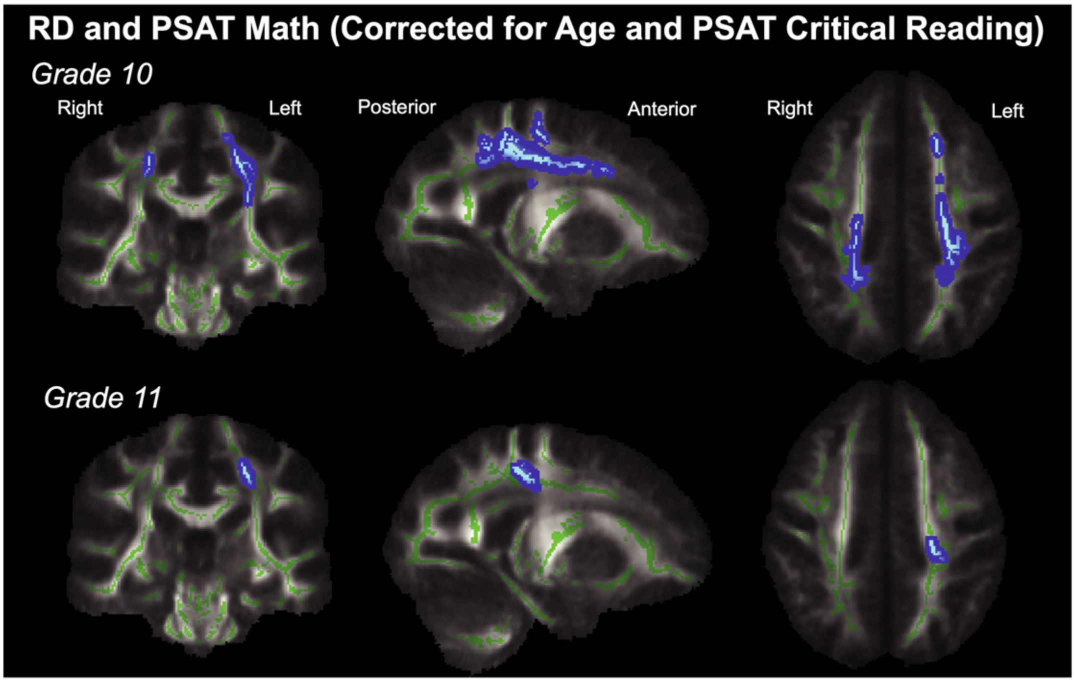

Fig. 3. White matter structures showing a negative correlation between RD and PSAT Math scores in Grade 10 and Grade 11. Correlations were corrected for chronological age and PSAT Critical Reading scores. Reported correlations are TFCE corrected where $p<.05$. The statistical map is overlaid onto the mean FA skeleton (green) and the mean FA map of all the subjects. There were no positive correlations between RD and PSAT Math scores.

these masks. PSAT Critical Reading scores in Grades 10 and 11 were then correlated with the extracted mean FA and RD values. These analyses revealed that PSAT Critical Reading from Grade 10 did not significantly correlate with the mean FA extracted from the cluster in Grade 10 $r(28)=-.11$, $p>.05$ or with the RD clusters from Grade 10 $r(28)=-.15$, $p>.05$. PSAT Critical Reading scores from Grade 11 did not significantly correlate with the mean FA extracted from the cluster in Grade 11 $r(28)=.15$, $p>.05$, nor did they correlate with RD cluster from Grade 11 $r(28)=-.34$, $p>.05$. The absence of a correlation between PSAT Critical Reading and both FA and RD in the left parietal white matter regions demonstrates that the correlation revealed is strongly math specific rather than simply reflecting a relatively larger correlation with math compared to reading or indeed a third factor that is common to both reading and math, such as working memory.

Discussion

Is variability in an individual's brain structure related to that person's scholastic aptitude? Only a handful of studies have begun to chart the white matter microstructures associated with numerical and mathematical competence, and no study to date has investigated the white matter structures associated with broad, college readiness tests of mathematical abilities. The present study fills this knowledge gap by revealing an association between left parietal white matter and individual differences on the PSAT math test in a sample of high-school seniors. These relationships were identified using stringent whole brain analyses and thus reveal those white matter microstructures which are most strongly related to individual differences in math achievement. While many regions are correlated with mathematical performance, left parietal microstructures predicted math performance on the PSAT at the most stringent thresholds and across two diffusion parameters.

Therefore, these findings significantly replicate and extend earlier research by demonstrating that left parietal white matter is most strongly related to mathematical performance, even when using a college-readiness test to assess high-level mathematical abilities. Furthermore, the present results extend previous research on the white matter correlates of mathematical competence in typically developing individuals by investigating multiple diffusion parameters to explain FA-math score correlations. Left parietal white matter was consistently related to PSAT math scores across two grades and across two diffusion parameters, FA and RD. Higher FA is related to increased myelination, axonal packing, and fiber coherence (Basser et al., 1994; Beaulieu, 2002) and thus we can infer that greater white matter integrity in the left parietal cortex of participants with higher PSAT math scores might be driven by such neuroanatomical factors. Since both PSAT Critical Reading scores and chronological age were used as covariates in the above analyses, the observed correlations can be considered to be specific to individual differences in math achievement. The specificity of left parietal white matter to mathematical skills is highlighted by the fact that PSAT Critical Reading scores did not correlate with FA or RD in this region. Therefore, domain-general processes that are shared by these two skills (i.e. working memory) are unlikely to account for these correlations.

These results also demonstrate the importance of correcting for factors such as chronological age and reading. The critical role played by covariates can be seen from the first analysis where, when age and PSAT Critical Reading were not included as covariates, many white matter microstructures were correlated with PSAT Math scores. Yet, once these variables were taken into account, fewer microstructures predicted mathematical competence. When comparing the analyses at the more stringent threshold of $p<.01$, only left parietal white matter predicted mathematical competence once chronological age and PSAT Critical Reading were controlled for, while many additional regions remained in the analysis without these covariates. Additional regions could be related to the effects of age, PSAT Critical Reading, or an interaction between the two. They may also be related to more domain-general processes that are shared by complex skills such as those tapped by the critical reading and math PSAT subtests. Apart from one study (Tsang et al., 2009), studies examining the white matter correlates of math achievement in typically developing individuals have not controlled for other cognitive abilities such as reading skills. In sum, using appropriate covariate is useful in determining the unique variance associated with mathematical skills and can have a considerable impact on significant regions.

The finding that radial but not axial diffusivity is related to individual differences in PSAT math scores further constrains our understanding of the relationship between white matter microstructure and math skills. The negative correlation between RD and math scores in left parietal white matter suggests that participants with higher RD in this region tended to have lower PSAT math scores. The reported results therefore replicate and significantly extend previous research by showing that correlations between FA and math achievement may be driven by changes in RD. This findings conflict with the results from Lebel et al. (2010), which suggest axial, but not radial diffusivity, explained the correlations between FA and math scores in their study. However, these differences may largely be a result of differences in populations (typical versus atypical). It should also be noted that in Grade 10, a correlation between RD in right parietal white matter and PSAT math was found. Thus while the evidence predominantly suggests an association between PSAT math scores and RD in the left hemisphere (since no right parietal correlations were found in Grade 11 and correlations with left parietal RD were found in both Grades 10 and 11), it should be acknowledged that the lateralization of correlations is not entirely clear-cut and the right parietal white matter microstructure may play some role in mathematical competence. However, the present results, as well as those from other studies discussed above, clearly show that this association is less consistent than the association between math performance and left parietal white matter.

There are likely many neuroanatomical factors that contribute to higher or lower RD, however, RD may be more sensitive to sources of anisotropy such as myelination when compared to AD. For example, reduced myelination can cause increases in RD but have no effect AD (Song et al., 2002). Consequently, the relationship between RD and math performance supports the interpretation that individual differences in neuroanatomical structures, such as myelination of left parietal white matter, may be associated with broad math competence. Notwithstanding, it is important to emphasize that there is no evidence for a one-to-one relationship between myelination and RD and therefore RD may reflect myelination as well as other white matter characteristics.

In previous studies, left parietal white matter integrity has been linked with mathematical skills, however, these studies have used basic measures such as simple arithmetic problems, and have not examined more complex, educationally relevant mathematical skills. For example, Tsang et al. (2009) found a relationship between FA in the anterior left superior longitudinal fasciculus and approximate addition, but not with exact addition or simple math facts. In a sample of 6–8 year old children, van Eimeren et al. (2008) found a positive correlation between written exact calculation problems and the left superior corona radiata, and Lebel et al. (2010) reported that FA the left corticospinal tract and the left superior longitudinal fasciculus were related to math word problems in children with fetal alcohol spectrum disorder. In accordance with our findings, these studies have predominantly found left-lateralized correlations between white matter integrity and mathematical skills. Our results, however, are the first to demonstrate that these white matter tracts are not only important in basic mathematical skills, but also for more complex tasks such as geometry, algebraic equations, and complex arithmetic. These findings suggest that higher-level mathematical abilities are related to white matter structures similar to those correlated with skills such as single digit arithmetic and approximate calculation. Our results therefore support the hypothesis that complex mathematical skills likely depend upon a solid foundation of basic numeracy skills. Left parietal white matter may support the acquisition of these skills and thereby provide the neuroanatomical scaffold for successful learning of higher-level math skills of the kind that are measured by the PSAT Math test.

Voxels spanning several tracts were associated with mathematical competence, including the left superior longitudinal fasciculus, left corticospinal tract, and left superior corona radiata. Further research will need to use analyses with greater anatomical specificity to determine the relative importance of these tracts for mathematical processing. The corona radiata has reciprocal connections to many areas the cortex and the corticospinal tract has descending projections to the brainstem from the motor, somatosensory, and parietal cortex (Oishi et al., 2011). The superior longitudinal fasciculus has projections to frontal, parietal, and temporal lobes (Oishi et al., 2011). It is important to contextualize the results in terms of connectivity since the above-mentioned tracts connect many cortical regions. Indeed, our results suggest that connectivity between regions is strengthened in individuals who show higher math performance and that transfer of information to and from regions that are critical for number processing in the left parietal cortex is therefore likely enhanced.

A large body of neuropsychological and functional neuroimaging literature provides convergent evidence for left-hemisphere lateralization of the parietal cortex for symbolic mathematical processing. Acquired brain damage in the left parietal cortex has long been linked to deficits in calculation (Gerstmann, 1940) and many functional neuroimaging studies have reported left hemisphere lateralization in adults during calculation (Chochon et al., 1999; Pinel and Dehaene, 2010). Furthermore, in a developmental study, Rivera et al. (2005) found that activation of the left parietal cortex during arithmetic problem solving is positively correlated with chronological age, suggesting that the left parietal cortex becomes specialized for mathematical tasks over the course of development (Rivera et al., 2005). Left hemisphere lateralization may be a result of exact calculation being scaffolded on verbal systems (Dehaene et al., 1999). The current DTI findings are highly congruent with a range of evidence suggesting specialization of functional and anatomical circuits in the left parietal cortex for mathematical skills, and further support the triple-code model (Dehaene et al., 2003).

The fact that math scores correlate with left parietal white matter over and above the PSAT critical reading test may appear surprising, given that previous studies have shown an association between individual differences in reading scores and left-hemisphere tracts (Klingberg et al., 2000; Niogi and McCandliss, 2006). However, in those studies measures of foundational reading competencies, such as phonological awareness, were used. The PSAT critical reading subtest assesses complex language processing (reading comprehension, logic-based sentence completion, and understanding words in context) and thus represents a broad test of linguistic competencies which cannot readily be compared to basic phonological processing. In this way the PSAT critical reading serves a control measure for a broad set of cognitive abilities, rather than representing a test that measures the foundational skills underlying reading ability.

The present findings suggest that learning and education may produce plastic changes in white matter integrity. Mouse models have shown that increasing or decreasing electrical activity in neurons modulates myelinogenesis (Demerens et al., 1996). Myelomodulation is experience dependent (Markham and Greenough, 2004), for example, rats raised in enriched environments have an increased number of myelinated axons in the corpus callosum (Juraska and Kopcik, 1988). It has been proposed that through experience, changes in myelin may optimize information processing (Fields, 2008). Indeed, enriched environments in pre-term infants results in greater white matter integrity and corresponds with improved performance on behavioral tests (Als et al., 2004). Relatedly, Scholz et al. (2009) have demonstrated experience dependent changes in FA following training in adults, and Bengtsson et al. (2005) showed that the number of hours practicing piano positively correlated with FA in motor tracts. In view of this body of findings, one plausible explanation for the relationship between PSAT math scores, FA, and RD in the left parietal cortex is experience dependent plasticity. White matter in this region may become reorganized as a function of acquiring skills over developmental time. This reorganization may be reflected in individual differences in FA and RD. Experimental studies will need to further elucidate how learning or training mathematical skills relates to white matter plasticity and what influences individual differences.

There are several important considerations that need to be noted when interpreting these findings. First, the cluster in left parietal white matter spans three white matter tracts (superior longitudinal fasciculus, corticospinal tract, and the superior corona radiata), therefore, crossing fibers may play a role in these correlations. Furthermore, only one or two of these tracts may be contributing to this correlation. The methods used in the present study did not allow us to determine whether one or all three tracts are important for mathematical processing. However, this could be addressed in future studies with other diffusion models that takes into account more than one primary diffusion direction or methods such as tractography, which can more easily delineate specific tracts and anatomical regions.

A second consideration is that the voxelwise analyses conducted in this study only show regional correlations with white matter and cognitive measures. Consequently, it is difficult to interpret how individual differences in math achievement are related to connectivity between regions. Finally, we hypothesize that left parietal microstructures become increasingly specialized with the acquisition of mathematical skills. However, the present findings cannot disambiguate between the relative contribution of genetic and environmental factors. Longitudinal and training studies will be needed to further clarify this interaction.

Conclusions

In conclusion, our findings suggest that the integrity of white matter microstructures in the left hemisphere is critical for complex mathematical processing. Moreover, the present results demonstrate that the brain–behavior relationships observed in previous studies are not restricted to basic number processing but remain evident when using measures of higher-level mathematical abilities. Later mathematical abilities are built upon more basic numeracy skills, and white matter in the left parietal cortex may support the development and acquisition of these complex skills. Individual differences in FA and RD may reflect variability in experience dependent plasticity over the course of learning and development. To our knowledge, this is the first study to show that individual differences in white matter are associated with mathematical abilities as measured by a nationally administered, educationally relevant test that predicts college performance and influences admittance. The current study supports and extends research on the functional and anatomical correlates of math and number processing, and provides novel evidence for the importance of left parietal circuits in complex, educationally-relevant mathematical skills.

Acknowledgments

We thank the participants for their invaluable time and contribution to this study. The research reported in this paper was funded by operating grants from the Natural Sciences and Engineering Council of Canada, and the Canadian Institute of Health Research to DA and an Ontario Graduate Scholarship to AM.

References

Als, H., Duffy, F.H., Mcanulty, G.B., Rivkin, M.J., Mulkern, R.V., Warfield, S.K., Huppi, P.S., et al., 2004. Early experience alters brain function and structure. Pediatrics 113 (4), 846–857.

Ansari, D., 2008. Effects of development and enculturation on number representation in the brain. Nat. Rev. Neurosci. 9 (4), 278–291 http://dx.doi.org/10.1038/nrn2334.

Arsalidou, M., Taylor, M.J., 2011. Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. Neuroimage 54 (3), 2382–2393 http://dx.doi.org/10.1016/j.neuroimage.2010.10.009.

Barnea-Goraly, N., Eliez, S., Menon, V., Bammer, R., Reiss, A.L., 2005. Arithmetic ability and parietal alterations: a diffusion tensor imaging study in Velocardiofacial syndrome. Cogn. Brain Res. 25 (3), 735–740 http://dx.doi.org/10.1016/j.cogbrainres.2005.09.013.

Basser, P.J., Mattiello, J., LeBihan, D., 1994. MR diffusion tensor spectroscopy and imaging. Biophys. J. 66 (1), 259–267 http://dx.doi.org/10.1016/S0006-3495(94)80775-1.

Beaulieu, C., 2002. The basis of anisotropic water diffusion in the nervous system — a technical review. NMR Biomed. 15 (7–8), 435–455.

Bengtsson, S.L., Nagy, Z., Skare, S., Forsman, L., Forssberg, H., Ullén, F., 2005. Extensive piano practicing has regionally specific effects on white matter development. Nat. Neurosci. 8 (9), 1148–1150 http://dx.doi.org/10.1038/nn1516.

Cantlon, J.F., Davis, S.W., Libertus, M.E., Kahane, J., Brannon, E.M., Pelphrey, K.A., 2011. Inter-parietal white matter development predicts numerical performance in young children. Learn. Individ. Differ. 21 (6), 672–680 http://dx.doi.org/10.1016/j.lindif.2011.09.003.

Chochon, F., Cohen, L., van de Moortele, P.F., Dehaene, S., 1999. Differential contributions of the left and right inferior parietal lobules to number processing. J. Cogn. Neurosci. 11 (6), 617–630.

Cohen Kadosh, R., Lammertyn, J., Izard, V., 2008. Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. Prog. Neurobiol. 84 (2), 132–147.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., Tsivkin, S., 1999. Sources of mathematical thinking: behavioral and brain-imaging evidence. Science 284 (5416), 970–974 http://dx.doi.org/10.1126/science.284.5416.970.

Dehaene, S., Piazza, M., Pinel, P., Cohen, L., 2003. Three parietal circuits for number processing. Cogn. Neuropsychol. 20 (3–6), 487–506 http://dx.doi.org/10.1080/02643290244000239.

Demerens, C., Stankoff, B., Logak, M., Anglade, P., Allinquant, B., Couraud, F., Zalc, B., et al., 1996. Induction of myelination in the central nervous system by electrical activity. Proc. Natl. Acad. Sci. U. S. A. 93 (18), 9887–9892.

Fields, R.D., 2008. White matter in learning, cognition and psychiatric disorders. Trends Neurosci. 31 (7), 361–370.

Gerstmann, J., 1940. Syndrome of finger agnosia, disorientation for right and left, agraphia, and acalculia. Arch. Neurol. Psychiatry 44 (2), 398–408.

Juraska, J.M., Kopcik, J.R., 1988. Sex and environmental influences on the size and ultrastructure of the rat corpus callosum. Brain Res. 450 (1–2), 1–8.

Klingberg, T., Hedehus, M., Temple, E., Salz, T., Gabrieli, J.D.E., Moseley, M.E., Poldrack, R.A., 2000. Microstructure of temporo-parietal white matter as a basis for reading ability: evidence from diffusion tensor magnetic resonance imaging. Neuron, 25(2). Elsevier, pp. 493–500 http://dx.doi.org/10.1016/S0896-6273(00)80911-3.

Lebel, C., Walker, L., Leemans, A., Phillips, L., Beaulieu, C., 2008. Microstructural maturation of the human brain from childhood to adulthood. NeuroImage, 40(3). Elsevier, pp. 1044–1055 http://dx.doi.org/10.1016/j.neuroimage.2007.12.053.

Lebel, C., Rasmussen, C., Wyper, K., Andrew, G., Beaulieu, C., 2010. Brain microstructure is related to math ability in children with fetal alcohol spectrum disorder. Alcohol. Clin. Exp. Res. 34 (2), 354–363 http://dx.doi.org/10.1111/j.1530-0277.2009.01097.x.

Markham, J.A., Greenough, W.T., 2004. Experience-driven brain plasticity: beyond the synapse. Neuron Glia Biol. 1 (4), 351–363 http://dx.doi.org/10.1017/s1740925x05000219.

Mazzocco, M.M.M., Devlin, K.T., 2008. Parts and "holes": gaps in rational number sense among children with vs. without mathematical learning disabilities. Dev. Sci. 11 (5), 681–691 http://dx.doi.org/10.1111/j.1467-7687.2008.00717.x.

Niogi, S., McCandliss, B.D., 2006. Left lateralized white matter microstructure accounts for individual differences in reading ability and disability. Neuropsychologia 44 (11), 2178–2188 http://dx.doi.org/10.1016/j.neuropsychologia.2006.01.011.

Oishi, K., Faria, A.V., Zijl, P.C.M.V., Mori, S., 2011. 2nd ed. MRI Atlas of Human White Matter, vol. 2010. Academic Press, London, p. 266.

Pinel, P., Dehaene, S., 2010. Beyond hemispheric dominance: brain regions underlying the joint lateralization of language and arithmetic to the left hemisphere. J. Cogn. Neurosci. 22 (1), 48–66 http://dx.doi.org/10.1162/jocn.2009.21184.

Rivera, S.M., Reiss, A.L., Eckert, M.A., Menon, V., 2005. Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex. Cereb. Cortex 15 (11), 1779–1790 http://dx.doi.org/10.1093/cercor/bhi055.

Rykhlevskaia, E., Uddin, L.L.Q., Kondos, L., Menon, V., 2009. Neuroanatomical correlates of developmental dyscalculia: combined evidence from morphometry and tractography. Front. Hum. Neurosci. 3, 51 http://dx.doi.org/10.3389/neuro.09.051.2009 (November).

Scholz, J., Klein, M.C., Behrens, T.E.J., Johansen-Berg, H., 2009. Training induces changes in white-matter architecture. Nat. Neurosci. 12 (11), 1370–1371 http://dx.doi.org/10.1038/nn.2412.

Smith, S.M., Nichols, T.E., 2009. Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. Neuroimage 44 (1), 83–98 http://dx.doi.org/10.1016/j.neuroimage.2008.03.061.

Smith, S.M., Jenkinson, M., Woolrich, M.W., Beckmann, C.F., Behrens, T.E.J., Johansen-berg, H., Bannister, P.R., et al., 2004. Advances in functional and structural MR image analysis and implementation as FSL. Neuroimage 23, 208–219 http://dx.doi.org/10.1016/j.neuroimage.2004.07.051.

Smith, S.M., Jenkinson, M., Johansen-Berg, H., Rueckert, D., Nichols, T.E., Mackay, C.E., Watkins, K.E., et al., 2006. Tract-based spatial statistics: voxelwise analysis of multi-subject diffusion data. NeuroImage 31 (4), 1487–1505.

Song, S.-K., Sun, S.-W., Ramsbottom, M.J., Chang, C., Russell, J., Cross, A.H., 2002. Dysmyelination revealed through MRI as increased radial (but unchanged axial) diffusion of water. Neuroimage 17 (3), 1429–1436 http://dx.doi.org/10.1006/nimg.2002.1267.

Till, C., Deotto, A., Tipu, V., Sled, J.G., Bethune, A., Narayanan, S., Arnold, D.L., et al., 2011. White matter integrity and math performance in pediatric multiple sclerosis: a diffusion tensor imaging study. Neuroreport 22 (18), 1005–1009 http://dx.doi.org/10.1097/WNR.0b013e32834dc301.

Tsang, J.M., Dougherty, R.F., Deutsch, G.K., Wandell, B.A., Ben-Shachar, M., 2009. Frontoparietal white matter diffusion properties predict mental arithmetic skills in children. Proc. Natl. Acad. Sci. U.S.A. 106 (52), 22546–22551 http://dx.doi.org/10.1073/pnas.0906094106.

van Eimeren, L., Niogi, S.N., McCandliss, B.D., Holloway, I.D., Ansari, D., 2008. White matter microstructures underlying mathematical abilities in children. Neuroreport 19 (11), 1117–1121 http://dx.doi.org/10.1097/WNR.0b013e328307f5c1.