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Diffusion properties of major white matter tracts in young, typically developing children

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ABSTRACT

Brain development occurs rapidly during the first few years of life involving region-specific changes in both gray matter and white matter. Due to the inherent difficulties in acquiring magnetic resonance imaging data in young children, little is known about the properties of white matter in typically developing toddlers. In the context of an ongoing study of young children with autism spectrum disorder, we collected diffusion-weighted imaging data during natural nocturnal sleep in a sample of young (mean age = 35 months) typically developing male and female (n = 41 and 25, respectively) children. Axial diffusivity, radial diffusivity, mean diffusivity and fractional anisotropy were measured at 99 points along the length of 18 major brain tracts. Influences of hemisphere, age, sex, and handedness were examined. We find that diffusion properties vary significantly along the length of the majority of tracks. We also identify hemispheric and sex differences in diffusion properties in several tracts. Finally, we find the relationship between age and diffusion parameters changes along the tract length illustrating variability in age-related white-matter development at the tract level.

Introduction

Early in life the human brain develops quickly. For example, brain volume expands from approximately 25% of adult size at birth to 75% by 2 years of age and 95% by 6 years of age (Knickmeyer et al., 2008; Pfefferbaum et al., 1994). MRI in children and adolescents has revealed rapid growth in both gray matter and white matter but with considerable regional variability (Giedd et al., 1996; Gilmore et al., 2007, 2012; Huang et al., 2006; Huttenlocher and Dabholkar, 1997; Jernigan et al., 1991; Nordahl et al., 2012; Peterson, 2003; Toga et al., 2006). Multiple factors such as age, sex and hemispheric asymmetry likely contribute to this variability in brain growth (Bonekamp et al., 2007; Eluvathingal et al., 2007; Giedd et al., 1997; Lebel and Beaulieu, 2009; Paus et al., 1999; Schmithorst et al., 2008; Trivedi et al., 2009). Accounting for these factors will produce a more thorough understanding of typical early brain development, which is critical for advancing research in neurodevelopmental disorders (Gabrieli, 2009; Honea et al., 2005; Qiu et al., 2008; Thiebaut de Schotten et al., 2011; Yeatman et al., 2012a).

The inherent difficulties in acquiring magnetic resonance imaging (MRI) data from young children means that relatively little information has been gathered regarding typical brain development prior to 5 years of age. Diffusion-tensor imaging (DTI) allows for detailed exploration of pediatric brain anatomy and has provided important information regarding white-matter development. While most major white matter tracts can be identified at birth, examination of tracts in young children has been somewhat lacking with rare exceptions (Dubois et al., 2006; Hermoye et al., 2006; Huang et al., 2006; Qiu et al., 2013; Trivedi et al., 2009; Weinstein et al., 2010; Wolff et al., 2012; Yap et al., 2011).

White matter tracts consist of thousands of axons entering and exiting at various points to reach specific targets. Thus, using a single diffusion parameter to characterize the entirety of a tract may mask potentially valuable information. To account for this variability and provide a detailed characterization of white matter tract structure during early childhood, we used newly available tractography software (Yeatman et al., 2012b) to analyze 18 white matter tracts in typically developing male and female toddlers ranging in age from 26 to 46 months. We quantified diffusion parameters along the length of each tract and identified localized differences while comparing tract properties between hemispheres and in relation to the age and gender of the subjects. We found substantial within-tract variability in many tracts as well as location specific sexual dimorphisms and differential effects of age on tract diffusion properties.

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Materials and methods

Participants

Participants were recruited through the M.I.N.D (Medical Investigation of Neurodevelopmental Disorders) Institute of the University of California, Davis (UCD), as part of the Autism Phenome Project. Diffusion imaging data were acquired from typically developing children including 41 males and 25 females (Table 1). Participants were recruited as part of a study on autism spectrum disorder, though children with ASD were not included in the present study. Inclusion criteria for the typically developing children included scores within ±1.5 standard deviations of the mean on all subscales of the Mullen Scales of Early Development. Handedness was assessed by means of behavioral examination. Exclusion criteria were physical contraindications to MRI, diagnosis with a pervasive developmental disorder, specific language impairment or any known developmental, neurological, or behavioral problems. All children were native English speakers. The UCD institutional review board approved this study, and informed consent was obtained from the parent or guardian of each participant.

Imaging procedures

MRI scans were acquired during natural nocturnal sleep at the UC Davis Imaging Research Center using a 3T Siemens Trio whole-body MRI system (Siemens Healthcare, Inc., Erlangen, Germany) equipped with an 8-channel head coil (Invivo, Inc., Gainesville, FL). The scanner room was decorated to be child-friendly with colorful wall hangings, pillows and stuffed animals. Earplugs and/or headphones were used to attenuate scanner noise and children were closely monitored during scanning. This approach has proven highly successful with a success rate of over 85% (Nordahl et al., 2008).

For all participants, images were obtained using a three-dimensional T1-weighted MPRAGE sequence (TR 2170 ms; TE 4.86 ms; matrix 256 × 256; 192 slices in the sagittal direction, 1.0 mm isotropic voxels, scan time: 8 m 6 s) and a diffusion-weighted, spin echo, echo planar imaging sequence ("ep2d_diff", number of slices: 72, slice thickness: 1.9 mm, slice gap: 0.0, matrix size: 128 × 128, voxel size: 1.9 mm isotropic, phase encoding direction: anterior to posterior (A > > P), phase partial Fourier: 5/8, TR: 11500, TE: 91, scan time: 6 m 56 s), with effective b-value 700 mm^2/s, 30 gradient directions, and five $b = 0$ images acquired at equally spaced intervals over the scan time. T2-weighted images were also obtained for clinical evaluation when possible (i.e. when the child remained asleep). All MPRAGE and available T2 scans were reviewed by a pediatric neuroradiologist and screened for significant, unexpected clinical findings.

Images were acquired from October 2007 to June 2011. In August 2009, the Siemens 3T Trio MRI system was upgraded to a Trio Total Imaging Matrix (TIM) MRI System running version VB15A operating system software. All the VA25A sequences were upgraded and mapped to their corresponding VB15A sequences with no parameter changes having an effect on image quality or appearance, except for the diffusion-weighted sequence. For this sequence, the spatial resolution, b-value, and diffusion gradient directions were preserved, but parameters were changed to reduce the geometric distortion of the images, and the impact of the geometric distortion on the image analysis. Specifically, the phase encoding direction was changed from 'anterior to posterior' (A > > P) to 'posterior to anterior' (P > > A), to eliminate tissue compression in the anterior temporal and frontal lobes, and the iPAT option (GRAPPA) was used with a factor 2 acceleration to permit shorter TE and reduced effective echo spacing for reduced geometric distortion at all voxels. The phase partial Fourier factor was increased from 5/8 to 6/8 to partially compensate for the factor 2 reduction in data acquired using GRAPPA. The use of GRAPPA allowed TE to be reduced from 91 ms to 81 ms, and echo spacing to be reduced from 0.83 ms to 0.69 ms. It also allowed TR to be reduced from 11,500 ms to 8500 ms, and scan time from 6 m 56 s to 5 m 23 s. Although the diffusion gradient parameters (directions and b-value) were not changed, the reduction in geometric distortion caused averaging (over the local tissue to determine each voxel value) to be different in the pre-upgrade versus post-upgrade images. Thus, there are likely to be differences in the diffusion parameters in regions with reduced geometric distortion. To control for these differences, we included MRI system upgrade status (pre-upgrade, post-upgrade) as a nuisance covariate for all statistical analyses involving diffusion parameters. In the current study, 29 scans (10 females, 20 males) were acquired before the scanner upgrade and 37 scans were acquired (15 females, 22 males) afterwards (Fisher's exact test, $p = 0.62$).

Table 1
Description of participants.

Continuous descriptors	Mean (SD)	Categorical descriptors	N (%)
Age in months	35.28 (4.71)	Left handed	6 (9.09)
Mullen's visual reception t-score	56.23 (11.04)	Right handed	58 (87.88)
Mullen's receptive language t-score	52.92 (7.28)	Undetermined	2 (3.03)
Mullen's expressive language t-score	55.49 (8.73)	Caucasian	51 (77.3)
Mullen's fine-motor t-score	50 (12.68)	Asian	6 (9.1)
		African-American	3 (4.5)
		Pacific-Islander	1 (1.5)
		Other	2 (3.0)
		Not specified	3 (4.5)

Image processing and diffusion tensor calculation

T1-weighted structural image preprocessing follows Nordahl et al. (2011) and included removal of nonbrain tissue using the Oxford Center for Functional MRI of the Brain (FMRIB) brain extraction tool (BET; Smith, 2002) and correction of main field (B0) inhomogeneities using the nonparametric nonuniform-intensity normalization method (N3; Sled et al., 1998). DTI data were processed using the VISTALab (Stanford Vision and Imaging Science and Technology) diffusion MRI software suite. The raw DTI DICOM images were converted to 4-D NifTI format and volumes and motion artifacts were excluded. DTI images were aligned to the motion-corrected mean of the non-diffusion weighted ($b = 0$) images using a rigid body algorithm. DTI images were then resampled to 2-mm isotropic voxels with eddy-current and motion correction using a 7th-order b-spline algorithm based on SPM5. VISTALab image processing software is available as part of the open-source mrDiffusion package available at http://white.stanford.edu/software/.

Diffusion tensors were fitted to the resampled DTI data using a least squares fit and the RESTORE algorithm that also removed outliers from the tensor estimation (Chang et al., 2005). The diffusion tensor model produces measures describing the diffusion characteristics of each voxel. Eigenvalues (λ1, λ2, λ3) from the diffusion tensor are used to compute axial diffusivity (λ1), radial diffusivity (λ2 + λ3/2), mean diffusivity (λ1 + λ2 + λ3/3) and fractional anisotropy ($\sqrt{(1/2)}\sqrt{((\lambda1-\lambda2)^2+(\lambda2-\lambda2)^2+(\lambda3-\lambda1)^2)} / \sqrt{(\lambda1^2+\lambda2^2+\lambda3^2)}$) (Pierpaoli and Basser, 1996). Axial diffusivity (AD) describes diffusion parallel to the principle diffusion direction (i.e. along the long axis of a fascicle of fibers) and has been related to changes in axon integrity such as during axonal degeneration (Kim et al., 2007; Song et al., 2003; Sun et al., 2006; Thomalla et al., 2004). Radial diffusivity (RD) describes diffusion perpendicular to the principle diffusion direction and is decreased with reduced axonal myelination or axon tract density (Song et al., 2002, 2003; Tyszka et al., 2006; Zhang et al., 2009). Mean diffusivity (MD) and fractional anisotropy (FA) are summative measures that describe average total diffusion and a normalized standard deviation of the three diffusion directions, respectively.

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Automatic fiber quantification

We used Automatic Fiber Quantification (AFQ) software tools to identify 18 white matter tracts in each participant's brain. AFQ and consists primarily of steps: (1) whole-brain tract tractography, (2) ROI-based tract segmentation and cleaning and (3) quantification. After ROI-based segmentation, fiber tracts were cleaned using a statistical outlier rejection algorithm. First each fiber in a fiber group is sampled to 99 equidistant nodes. Then the spread of fibers at each node is represented as a 3 dimensional Gaussian distribution and any fiber that is more than 5 standard deviation from the core (mean) of the tract is removed. The procedure is repeated until there are no more fiber outliers. Diffusion properties are then calculated along the trajectory of the fiber group by interpolating the image value (FA, MD, AD, RD) at each node along each fiber. Tract profiles of each parameter are then calculated as a weighted sum of each fiber's value at a given node where a fiber is weighted based on its Mahalanobis distance from the core or mean location of the tract. AFQ tractography yields tracts similar to those seen in other reports in this participant age range (Fig. 1, Huang et al., 2006; Trivedi et al., 2009; Wolff et al., 2012). Furthermore, tractography results generally match the overall shape and anatomical paths seen in older children and adults (Goodlett et al., 2009; Hermoye et al., 2006; Huang et al., 2006; Lebel et al., 2012). AFQ is described in greater detail in Yeatman et al. (2012b).

Because AFQ uses strict criterion for tract identification, it did not identify all 18 tracts in each participant. As might be expected, image quality was a significant determinant of AFQ's ability to segment and identify tracts, and there was greater success with scans acquired after the scanner and sequence update (see Imaging procedures section). Details regarding tract identification rates and their influence on the total N used in analysis are shown in Table 2.

For the most part, tract identification did not differ in the left and right hemispheres. However, both the cingulum and arcuate fasciculus had greater probability of identification in the left hemisphere than in the right (left cingulum 85%, right cingulum 71%, Fisher's exact test $p < 0.05$; left arcuate fasciculus 87%, right arcuate fasciculus 52%, Fisher's exact test $p < 0.001$). Difficulty in identifying the right arcuate fasciculus using tractography is a consequence of the right tract exhibiting higher curvature and greater partial voluming with the superior longitudinal fasciculus compared with the left arcuate fasciculus (Catani et al., 2007; Lebel and Beaulieu, 2009; Mishra et al., 2010; Yeatman et al., 2011). Laterality of cingulum diffusion parameters has been previously reported in adults (Gong et al., 2005a). The significant asymmetry in all four diffusion parameters for the cingulum likely contributed to the difference in identification rates and is discussed in more detail below.

Tract identification was also not influenced by participant sex with the exception of the right and left inferior longitudinal fascicles (ILF; Fisher's exact test, ps < 0.001). These tracts were identified less often in males than in females. Sex differences in diffusion parameters have been found in the ILF previously (Choi et al., 2010) and in the current study (see Effects of sex section). If diffusion is lower in males through much of this tract's bundle, this may lead to a greater chance of exclusion during tractography.

Statistical approach

For each subject, AD, RD, MD, and FA were calculated at 99 nodes between the two defining ROIs for each tract. For all differential analysis, separate three-way mixed-design analyses of co-variance (ANCOVA) were conducted for the continuous dependent variables (AD, RD, MD, FA). Hemisphere and nodes were used as repeated measures and sex as a between-group measure. For hemisphere analysis in the forceps major and minor nodes 1–49 were compared to nodes 50–99.

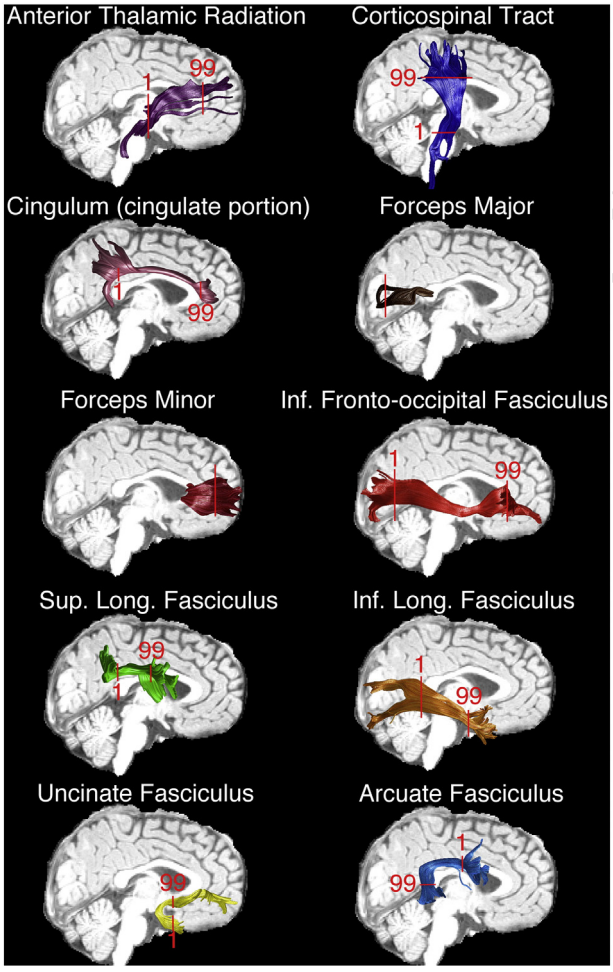

Fig. 1. White-matter tracts examined. AFQ tractography identifies major white matter tracts in children between 26 and 48 months. Single subject results are shown for each of the tracts used in the current analysis. In addition, red markers denoting the start (1) and termination (99) of nodal quantification are overlaid onto each tracts bundle. In the forceps major and minor quantification originated in the left hemisphere and proceeded to the right.

Table 2
Tract identification rates.

Tract name	Preupgrade scans (%)	Postupgrade scans (%)	Total N used in analyses
Left thalamic radiation	86.67	100.00	63
Right thalamic radiation	96.67	100.00	66
Left corticospinal	96.67	100.00	66
Right corticospinal	96.67	100.00	66
Left cingulum	66.67	100.00	57
Right cingulum	46.67	91.89	48
Forceps major	50.00	100.00	52
Forceps minor	100.00	100.00	67
Left inferior fronto-occipital	80.00	100.00	61
Right inferior fronto-occipital	83.33	100.00	62
Left inferior longitudinal	70.00	100.00	58
Right inferior longitudinal	66.67	94.59	55
Left superior longitudinal	93.33	97.30	64
Right superior longitudinal	96.67	100.00	66
Left uncinate	93.33	100.00	65
Right uncinate	96.67	100.00	66
Left arcuate	80.00	91.89	58
Right arcuate	56.67	48.65	35

Participant's age was included as a continuous covariate while handedness and scanner status were controlled.

Mauchly's test of sphericity (Mauchly, 1940) was used to test for violations of sphericity and the Greenhouse–Geisser correction (Greenhouse and Geisser, 1959) was applied when sphericity was violated. Follow-up one-way ANCOVAs and Bonferroni-corrected pairwise comparisons were used to further investigate significant main-effects and interactions identified in the omnibus tests. Because the repeated measure of nodes was nested within the repeated measure of hemisphere, pairwise comparisons of hemisphere mean differences (averaged across nodes) were considered useful and informative in the absence of significant omnibus hemisphere effects. For correlations between age and diffusion properties, partial correlations controlling for scanner upgrade status were used. For all analyses, results are expressed as mean ± SEM (standard error of the mean), and a p-value less than 0.05 was considered statistically significant.

Results

Effects of hemisphere

For all tracts except the forceps minor, significant effects of hemisphere were seen for most of the diffusion parameters (Fig. 2, Table 3). When significantly different, mean AD was generally higher in the right hemisphere, with the only exception being in the cingulum. Similarly, mean RD was usually higher in the right hemisphere. Mean MD was also higher in the right hemisphere for several tracts. Mean FA was higher in several left hemisphere tracts. It was higher in the right hemisphere only for the superior longitudinal fasciculus (SLF). Corrected comparisons between hemisphere diffusion parameter means are detailed in Table 3.

In every case in which FA was greater in one hemisphere, AD and/or RD were asymmetric as well. However, in the thalamic radiation and uncinate fasciculus, AD or RD was asymmetric without an asymmetry in FA. Due to the substantial between hemisphere variability indicated by these analyses, subsequent analyses reported below were conducted independently for each hemisphere.

Effects of nodes

For the majority of tracts, diffusion properties varied significantly along the length of the tract (Fig. 2). AD, RD and MD were significantly variable in 8, 6 and 10 tracts respectively. FA was variable in 4 tracts. Only the left inferior fronto-occipital fasciculus (IFOF), left and right inferior longitudinal fasciculi (ILF), and left and right superior longitudinal fasciculi (SLF) exhibited relative homogeneity along their length for all diffusion properties. Statistical comparisons for the effects of nodes on each tract are shown in Table 4.

Effects of sex

Male and female participants exhibited significant differences in the diffusion parameters in 4 tracts. The most prominent sex difference was seen in the left cingulum bundle (Fig. 3). AD in the cingulum was greater in males than in females (main effect of sex: $F(1,98) = 5.71$, $p < 0.05$). Corrected comparisons revealed that the AD differences were restricted mostly to two bands of nodes along the tract length; one caudal portion of the anterior cingulate and a second larger band adjacent to the posterior cingulate. RD was higher in females than in males (main effect of sex: $F(1,98) = 5.95$, $p < 0.05$). This was restricted to one large band of nodes near the posterior cingulate. The elevated AD in males and elevated RD in females also resulted in a sex difference in FA (main effect of sex: $F(1,98) = 9{,}93$, $p < 0.005$) with FA being higher in males than in females in both a small band at the anterior end of the tract and a larger band at its posterior portion.

Sex differences were also found in the right IFOF (Fig. 4). AD was higher in males (main effect of sex: $F(1,98) = 5.24$, $p < 0.05$). Although there was a small band of significantly different AD near the anterior portion of the IFOF, the largest band of difference was at the posterior end of the tract. Mean diffusivity was also higher in males in this location (interaction of nodes and sex: $F(1,2.38) = 2.95$, $p < 0.05$).

Additional sex differences were found in the left ILF and right uncinate fasciculus (Fig. 5). FA was higher in females in the left ILF in two distinct bands towards the anterior end of the tract (main effect of sex: $F(1,98) = 7.17$, $p < 0.05$). FA was also higher in females in the right uncinate in a band near the temporal end of the tract (interaction of nodes and sex: $F(1,4.47) = 2.69$, $p < 0.05$).

Two tracts had additional interactions involving participant sex. In the cingulum, the interaction between hemisphere and sex was significant ($F(1,98) = 4.69$, $p < 0.05$) with females exhibiting less laterality than males (females: left hemisphere 0.41 ± 0.10, right hemisphere 0.39 ± 0.01; males: left hemisphere 0.48 ± 0.01, right hemisphere 0.041 ± 0.01). In the uncinate, the interaction between sex, hemisphere, and nodes was significant for RD ($F(1,5.49) = 2.97$, $p < 0.05$) and FA ($F(1,5.3) = 2.58$, $p < 0.05$). RD is lower in the right uncinate fasciculus compared with the left in the temporal portion of the tract and then becomes higher in the right uncinate compared with the left in females. In males, RD is higher in the right uncinate fasciculus compared with the left and then becomes lower compared with the left as the tract passes into the frontal lobe.

Age as a covariate of interest

We found age to be a significant contributor to variation in 5 tracts: the forceps minor, left IFOF, left SLF, left uncinate fasciculus, and right arcuate fasciculus. For the forceps minor, the left IFOF and the left uncinate fasciculus, age was significant as a main effect. In the left and right arcuate fasciculi, age emerged in a significant interaction with nodes. We chose to examine the correlations between age and diffusion parameters in these tracts.

Examining partial correlations at each node (scanner status and handedness controlled) revealed substantial variation in the correlation between age and diffusion parameters (Fig. 6). In the forceps minor, RD, AD and MD were negatively correlated with age. However, the relationship was particularly strong near where the forceps minor passes through the genu of the corpus callosum. In the left IFOF, FA exhibited a variable but mostly positive relationship with age; the strongest correlations were near the frontal end of the tract. AD in the left SLF was both negatively and positively correlated with age with a strong positive correlation near the frontal termination of the tract. In the left uncinate fasciculus, MD is most strongly correlated with age as the tract begins to leave the temporal lobe and passes near the IFOF. The right arcuate exhibited highly variable correlations with age along the tract length for RD, MD and FA. For each diffusion parameter in the arcuate fasciculus, correlations reversed in sign near the temporo-parietal termination point of the tract.

Participant handedness as a covariate

Evidence for a handedness effect on white-matter diffusion parameters in young children is limited. However, handedness effects have been revealed in adults in some tracts (Gong et al., 2005a). We included handedness as a covariate to control for potential confounding effects without specific hypotheses. Handedness emerged as a significant covariate in seven tracts for various diffusion parameters: FA in the right corticospinal tracts, MD in the left cingulum, FA, AD, MD and RD in the forceps minor, FA in the right IFOF, FA in the right ILF, FA in the right uncinate and RD, MD in the right arcuate. In general, FA tended to be higher and MD lower in right handed subjects compared with left handed subjects.

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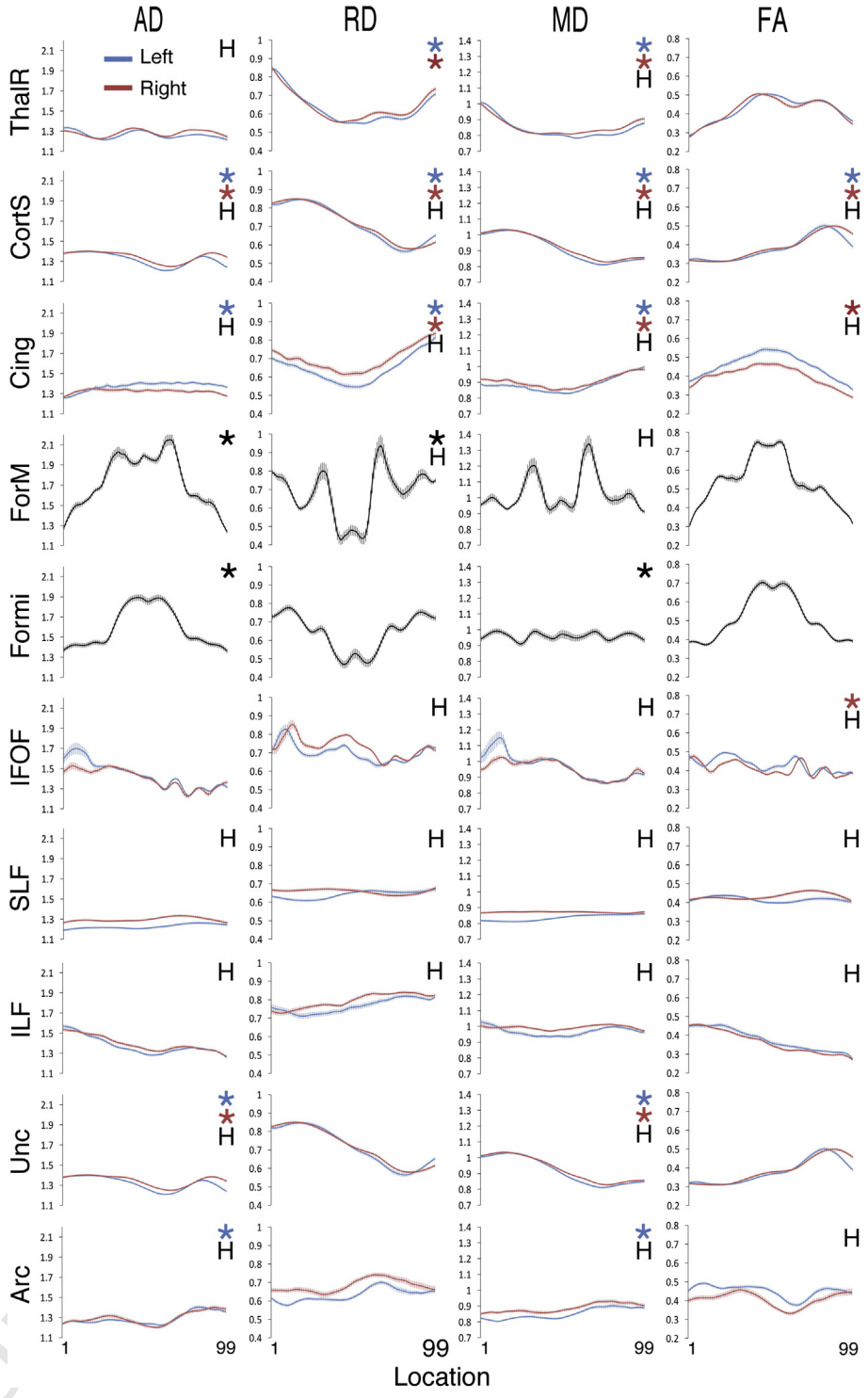

Fig. 2. Diffusion parameters vary along the length of tracts. Average diffusion parameter plots in 18 tracts from typically developing children. Each plot depicts AD, RD, MD or FA between the 1st and 99th nodes of each tract named at left. Tract names are abbreviated as follows: ThalR = thalamic radiations, CortS = corticospinal tracts, Cing = cingulum, ForM = forceps major, Formi = forceps minor, IFOF = inferior fronto-occipital fasciculus, SLF = superior longitudinal fasciculus, ILF = inferior longitudinal fasciculus, Unc = uncinate fasciculus, Arc = arcuate fasciculus. On each plot, "H" denotes a significant difference between the left and right hemispheres and * indicates a significant effect of location for the diffusion parameter plotted.

Discussion

Differences in the progression of tract diffusion parameters are thought to reflect differential rates of axonal refinement, packing and myelination as part of overall white matter maturation (Beaulieu, 2002; Song et al., 2002, 2005; Takahasi et al., 2000; but see Wheeler-Kingshott et al., 2009). However, few studies have investigated the variation in diffusion parameters along the length of major fasciculi in relation to hemisphere and sex before the age of 5, a time when the brain is changing rapidly. We found diffusion parameter variability related to sex, hemisphere and age in multiple white matter tracts within a sample of 26–46 month old typically developing young children. In

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Table 3
Hemisphere differences in tract diffusion properties.

Tract name	Left hemisphere Mean (95% CI)	Right hemisphere Mean (95% CI)	Pairwise p-value
Thalamic radiation			
AD*	1.26 (1.25–1.27)	1.28 (1.27–1.29)	0.00
RD	0.63 (0.62–0.63)	0.63 (0.62–0.64)	0.20
MD*	0.84 (0.83–0.85)	0.85 (0.84–0.85)	0.01
FA	0.43 (0.42–0.43)	0.43 (0.42–0.44)	0.60
Corticospinal tract			
AD*	1.42 (1.41–1.43)	1.49 (1.47–1.50)	0.00
RD*	0.55 (0.54–0.56)	0.62 (0.60–0.63)	0.00
MD*	0.84 (0.83–0.85)	0.91 (0.90–0.92)	0.00
FA*	0.55 (0.54–0.56)	0.52 (0.51–0.53)	0.00
Cingulum			
AD*	1.38 (1.35–1.40)	1.32 (1.30–1.34)	0.00
RD*	0.64 (0.62–0.65)	0.69 (0.68–0.71)	0.00
MD*	0.88 (0.87–0.90)	0.90 (0.89–0.92)	0.01
FA*	0.46 (0.45–0.47)	0.40 (0.39–0.41)	0.00
Inferior fronto-occipital			
AD	1.41 (1.40–1.43)	1.42 (1.40–1.44)	0.51
RD*	0.70 (0.69–0.71)	0.73 (0.72–0.74)	0.00
MD*	0.94 (0.93–0.95)	0.96 (0.95–0.97)	0.00
FA*	0.43 (0.42–0.44)	0.41 (0.40–0.42)	0.00
Superior longitudinal			
AD*	1.23 (1.21–1.24)	1.30 (1.28–1.32)	0.00
RD*	0.64 (0.63–0.66)	0.66 (0.65–0.67)	0.01
MD*	0.84 (0.82–0.85)	0.87 (0.86–0.89)	0.00
FA*	0.42 (0.40–0.43)	0.43 (0.42–0.44)	0.01
Inferior longitudinal			
AD*	1.37 (1.36–1.39)	1.39 (1.38–1.41)	0.02
RD*	0.75 (0.74–0.76)	0.79 (0.78–0.80)	0.00
MD*	0.96 (0.95–0.97)	0.99 (0.98–1.00)	0.00
FA*	0.39 (0.38–0.39)	0.36 (0.36–0.37)	0.00
Uncinate			
AD*	1.32 (1.30–1.33)	1.35 (1.34–1.36)	0.00
RD	0.71 (0.70–0.72)	0.72 (0.71–0.73)	0.31
MD*	0.91 (0.91–0.92)	0.93 (0.92–0.93)	0.00
FA	0.38 (0.38–0.39)	0.39 (0.38–0.40)	0.05
Arcuate			
AD	1.30 (1.27–1.32)	1.29 (1.27–1.31)	0.40
RD*	0.63 (0.61–0.65)	0.68 (0.66–0.70)	0.00
MD*	0.85 (0.84–0.87)	0.88 (0.87–0.90)	0.00
FA*	0.46 (0.44–0.47)	0.41 (0.39–0.42)	0.00
Forceps major			
AD	1.75 (1.70–1.79)	1.73 (1.68–1.77)	0.08
RD*	0.64 (0.61–0.68)	0.71 (0.66–0.75)	0.04
MD*	1.01 (0.97–1.05)	1.05 (1.00–1.09)	0.04
FA	0.57 (0.55–0.59)	0.52 (0.50–0.54)	0.10
Forceps minor			
AD	1.61 (1.60–1.63)	1.63 (1.61–1.64)	0.74
RD	0.66 (0.64–0.67)	0.65 (0.63–0.66)	0.34
MD	0.96 (0.96–0.99)	0.98 (0.96–0.99)	0.35
FA	0.52 (0.51–0.53)	0.53 (0.52–0.54)	0.32

* Denotes a significant between hemisphere differences with $p < 0.05$.

addition, we found that diffusion parameters vary substantially along the length of a single fiber tract.

Diffusion parameters vary along tract length in young children

Previous reports have measured integrated mean diffusion parameters across the entire tract within the age range reported here (Fletcher et al., 2010; Hermoye et al., 2006; Lebel et al., 2012; Trivedi et al., 2009). However, this is the first report to describe within-tract variability at this age. The variations in diffusion at different sample positions likely reflect a combination of factors including variations in myelination, axonal density, and axonal diameter as well as the influence of tract curvature, partial voluming effects and the entrance and exit of smaller axonal bundles from the larger tract (Fig. 7). Diffusion properties are affected by biological properties of the axons in a voxel (e.g. myelination, axonal density and axonal diameter) as well as the geometric configuration of the axons (e.g. curvature, directional coherence and crossing fiber tracts). We find that diffusion properties vary substantially along the trajectory of a fascicle. For example, in the forceps minor, AD is low as the tract terminates at various targets within the frontal lobe and rises sharply as the tract forms a cohesive bundle while crossing the midline via the genu of the corpus callosum (Fig. 2). Similarly, RD is high in the thalamic radiation where the tract originates, but drops considerably as the tract enters the dense collection of myelinated white matter in the anterior limb of the internal capsule and rises again as the tract enters the cortical gray matter. Since these measurements were made in young children it is likely that some of the variation in diffusion properties is due to variation in the amount of myelin along the tract length as well (Dubois et al., 2006). In addition, white matter contains crossing, branching and merging fiber bundles and these geometric properties will have a substantial impact on the diffusion properties of a voxel (Jones, 2002). For example a bundle of axons that crosses through the main fascicle will hinder diffusion parallel to the fascicle but allow more diffusion perpendicular to the fascicle (Yeatman et al., 2012b). This will also lead to a reduction in fractional anisotropy. We believe that a portion of the variance in diffusion properties that we observe along the length of these fascicles is the product of crossing, merging and branching fibers.

The different tract profiles for AD, RD, MD and FA emphasize the importance of examining more than one diffusion parameters. For example, in the corticospinal tract, AD and RD are both elevated while the tract is within the brain stem. At this level, the corticospinal tract is mostly surrounded by transverse fibers of the pons which travel perpendicular to the corticospinal tracts. Partial voluming with these tracts likely produces the elevated RD seen at this point, which in combination with high AD, results in low FA values. AD values peak again where the corticospinal tract enters the internal capsule. However, radial diffusivity there remains low. This is likely because the corticospinal tract makes up the majority of the anterior portion of the posterior limb of the internal capsule resulting in less perpendicular diffusion. As a result, FA is highest at this point in the corticospinal tract. Patterns of variability within the four diffusion properties are informative in other tracts as well.

Sex differences in diffusion parameters

We found sexual dimorphism in portions of 4 tracts: the left cingulum, the right IFOF, the left ILF, and the right uncinate. The cingulum exhibited the most dramatic sex differences with significant effects for AD (males > females), RD (females > males) and FA (males > females; Fig. 3). Sexual dimorphism of cingulum diffusion parameters is seen in adults (Hsu et al., 2008; Huster et al., 2009; Rametti et al., 2011) and over lifespan development (Kochunov et al., 2012; Lebel and Beaulieu, 2011; Lebel et al., 2012; Trivedi et al., 2009). Consistent with the current data, the majority of reports find that FA is higher in males (but see Schneiderman et al., 2007) and the sexual dimorphism appears most often in the left cingulum. The cingulum is involved in attention, emotion and memory, and sexual dimorphisms in regions connected to the cingulum such as the cingulate cortex and the amygdala are also common (Biver et al., 1996; Giedd et al., 1997; Gur et al., 1995; Johnson et al., 2008; Merke et al., 2003; Paus et al., 1996; Pujol et al., 2002; Wrase et al., 2003).

Sexual dimorphism was also seen in the IFOF (Fig. 4). The IFOF has been linked to semantic understanding (Duffau, 2008), reading (Catani and Mesulam, 2008) and visual processing (Fox et al., 2008). Reduced mean RD in adult females has previously been reported in the right IFOF (Eluvathingal et al., 2007). Interestingly, increased FA in adult males has been reported in a voxel cluster near the location of

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Table 4
Analysis of variation in diffusion properties along tract length.

	Effect of nodes			
Tract name	AD	RD	MD	FA
Left thalamic radiation	$F = 1.11, p = 0.36$	$F = 5.17, p < 0.00^*$	$F = 4.13, p < 0.00^*$	$F = 2.27, p = 0.07$
Right thalamic radiation	$F = 1.26, p = 0.28$	$F = 2.94, p = 0.02^*$	$F = 2.87, p = 0.02^*$	$F = 1.33, p = 0.26$
Left corticospinal	$F = 3.59, p < 0.00^*$	$F = 10.15, p < 0.00^*$	$F = 10.45, p < 0.00^*$	$F = 3.23, p = 0.01^*$
Right corticospinal	$F = 9.70, p < 0.00^*$	$F = 16.91, p < 0.00^*$	$F = 17.60, p < 0.00^*$	$F = 6.58, p < 0.00^*$
Left cingulum	$F = 2.39, p = 0.03^*$	$F = 2.99, p < 0.00^*$	$F = 5.23, p = 0.01^*$	$F = 0.78, p = 0.58$
Right cingulum	$F = 1.69, p = 0.12$	$F = 4.04, p < 0.00^*$	$F = 4.86, p < 0.00^*$	$F = 2.06, p = 0.05^*$
Forceps major	$F = 2.44, p = 0.02^*$	$F = 1.30, p = 0.03^*$	$F = 1.52, p = 0.19$	$F = 1.63, p = 0.12$
Forceps minor	$F = 2.24, p = 0.04^*$	$F = 1.88, p = 0.10$	$F = 2.99, p = 0.01^*$	$F = 0.84, p = 0.54$
Left inferior fronto-occipital	$F = 1.30, p = 0.26$	$F = 0.30, p = 0.88$	$F = 0.52, p = 0.66$	$F = 0.99, p = 0.44$
Right inferior fronto-occipital	$F = 1.85, p = 0.14$	$F = 1.94, p = 0.13$	$F = 1.86, p = 0.15$	$F = 2.34, p = 0.02^*$
Left superior longitudinal	$F = 0.63, p = 0.61$	$F = 1.18, p = 0.32$	$F = 1.32, p = 0.27$	$F = 0.75, p = 0.52$
Right superior longitudinal	$F = 0.71, p = 0.55$	$F = 2.29, p = 0.08$	$F = 2.35, p = 0.08$	$F = 0.63, p = 0.39$
Left inferior longitudinal	$F = 0.63, p = 0.63$	$F = 1.09, p = 0.37$	$F = 0.71, p = 0.59$	$F = 1.45, p = 0.21$
Right inferior longitudinal	$F = 1.54, p = 0.19$	$F = 0.86, p = 0.50$	$F = 0.97, p = 0.42$	$F = 1.97, p = 0.06$
Left uncinate	$F = 4.46, p < 0.00^*$	$F = 1.13, p = 0.34$	$F = 3.77, p < 0.00^*$	$F = 1.50, p = 0.19$
Right uncinate	$F = 3.00, p = 0.02^*$	$F = 2.04, p = 0.08$	$F = 3.62, p = 0.01^*$	$F = 1.08, p = 0.37$
Left arcuate	$F = 3.56, p < 0.00^*$	$F = 0.95, p = 0.44$	$F = 3.40, p = 0.01^*$	$F = 0.78, p = 0.57$
Right arcuate	$F = 1.12, p = 0.35$	$F = 1.26, p = 0.28$	$F = 2.19, p = 0.05$	$F = 0.99, p = 0.43$

* Denotes a significant between node differences with $p < 0.05$.

the smaller band of sexually dimorphic AD seen in children (Fig. 4; Rametti et al., 2011). While not identical to our results, these findings suggest that sex differences persist in the IFOF. Furthermore, the large posterior band of sex differences approximates the point where the IFOF sharply radiates to eventual terminations in parietal, occipital and posterior temporal cortices. There are sexual dimorphisms in cortical thickness (females > males) in the right inferior parietal and posterior temporal regions (Sowell et al., 2007), which may be related to sexual dimorphism in this tract.

We also found a sex difference in FA within the left ILF (Fig. 5). The ILF consists of long and short tracts with the more lateral short tracts connecting adjacent nonpolar temporal gyri. The sex differences in FA may be due to differing amounts of short tracts entering or exiting the tract near the two bands of significant differences. Overall RD and MD are lower in the ILF of adolescent females compared with males (Eluvathingal et al., 2007), and two previous lifespan reports also found sex differences in ILF FA with the same (Hasan et al., 2010) and opposite (Lebel et al., 2012) direction as the current data (male FA > female). Face recognition and emotional memory which are associated with the ILF and its connected regions (Fox et al., 2008; Philippi et al., 2009) also sexually dimorphic with women outperforming men on face recognition and emotional memory tasks (Cahill et al., 1996; Cellerino et al., 2004; Lewin and Herlitz, 2002).

The right uncinate fasciculus was sexually dimorphic as well (Fig. 5). Two other lifespan studies starting at 5 years found higher mean FA in the uncinate fasciculus of males compared with females suggesting that this sex difference is persistent (Lebel and Beaulieu, 2011; Lebel et al., 2012). Like the SLF and cingulum, the uncinate connects polar temporal lobe areas, including the amygdala, to cortical regions. Interestingly, a study examining 12-year-old male and female children born preterm found a group by sex interaction using ROI analysis of the right uncinate fasciculus. In control participants, males had higher FA compared with females, but in the preterm group, males had lower FA. Verbal IQ and Peabody Picture Vocabulary Test-Revised scores were correlated with both right and left uncinate fasciculus scores in the preterm male group (Constable et al., 2008).

These findings demonstrate that multiple fiber tract diffusion parameter sexual dimorphisms are present in young children. The overall pattern of tract differences suggest sexual dimorphism in connections between visual and emotion/memory centers (ILF), visual and higher-order processing centers (IFOF), emotion/memory centers and higher-order processing centers (uncinate, cingulum). Most of the cortical and sub-cortical targets of these tracts are sexually dimorphic in adults and exhibit high levels of steroid hormone receptor concentration in animal models (see Goldstein et al., 2001). We suspect that these tract sexual dimorphisms are the result of organizational actions of steroid

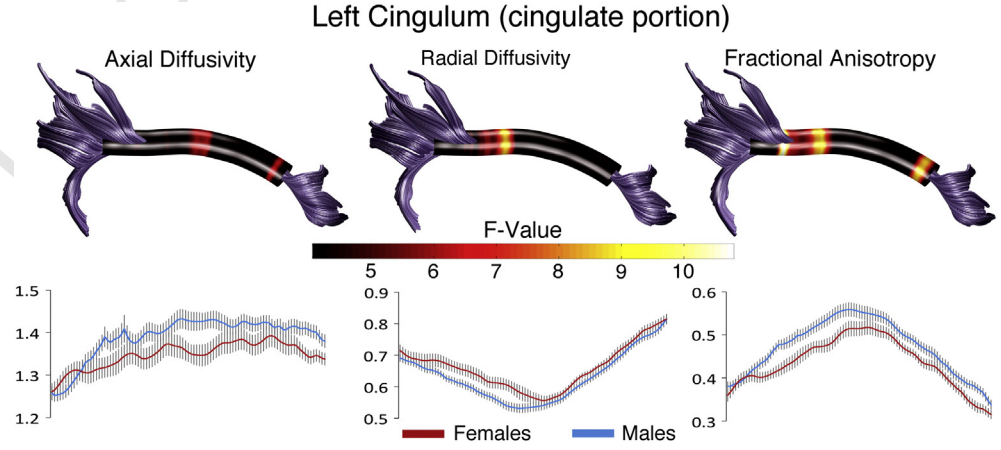

Fig. 3. Sex differences in the left cingulate portion of the cingulum. Tract profiles illustrating sex differences in AD, RD, and FA along the cingulum in typically developing male and female children. Color bar indicates F statistic values from Bonferroni-corrected analyses of covariance conducted at each location along the tract length. Significant comparisons are indicated by non-black regions. Plots for AD, RD and FA in males and females are presented below each tract profile.

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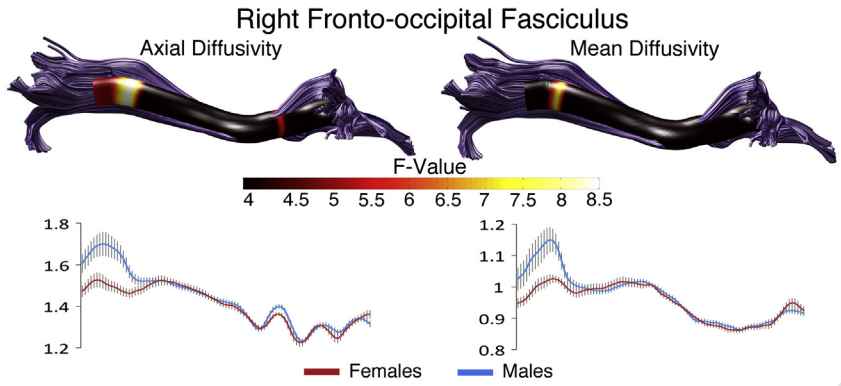

Fig. 4. Sex differences in the right inferior fronto-occipital fasciculus. Tract profiles illustrating sex differences in AD and MD along the right OFF in typically developing male and female children. Color bar indicates F statistic values from Bonferroni-corrected analyses of covariance conducted at each location along the tracts length. Significant comparisons are indicated by non-black regions. Plots for AD and MD in males and females are presented below each tract profile.

hormones or sex chromosome genetics occurring in utero or during the perinatal hormone surge.

In addition, these sex differences are concentrated in select locations along the tracts. One possible explanation is that hormone sensitive gray matter regions produce sexually dimorphic axonal contributions to these tracts which manifest in diffusion parameter differences at these locations. Alternately, diffusion parameter sexual dimorphisms may be due to greater tract curvature or partial voluming with adjacent structures or even different rates of tract myelination. Sexual differentiation studies incorporating localized measures of diffusion in both younger and older children will produce a map of white matter sexual dimorphism emergence, which may be useful in understanding disorders with sex biases in the population.

Age effects in diffusion parameters

Age is known to be an important factor in measures of white matter diffusion. The few neonatal DTI studies available show considerable change in fiber tract diffusion parameters during neonatal life, but the rate of change appears to slow past 24 months (Hermoye et al., 2006; Huang et al., 2006; Trivedi et al., 2009). Lifespan development studies starting from age 5 describe increases in FA followed by a plateau for most tracts during early adulthood and a slow decline during old age with an opposite pattern for MD (Eluvathingal et al., 2007; Lebel and Beaulieu, 2011; Lebel et al., 2008, 2012; Schmithorst, 2009). Similar to results in older children, we found generally positive relationships between age and FA (Fig. 6; left IFOF, right arcuate) and mostly negative relationships between age and MD (Fig. 6; forceps minor, left uncinate).

Increasing FA with age is thought to be driven by decreasing RD as white matter become increasingly myelinated (Bonekamp et al., 2007; Eluvathingal et al., 2007; Hasan et al., 2010; Verhoeven et al., 2009; Westlye et al., 2010). This was the case in the right arcuate where RD and FA displayed opposing correlations with age. In the left IFOF, the only other tract to show a significant age effect for FA, the effect of age on RD approached significance for RD ($p = 0.069$).

The current data help bridge the age gap in our understanding of white matter in children and provide additional details in several tracts by illustrating that aging does not uniformly influence tract diffusion parameters. We suspect that other tracts undergo similar age-related changes along their length but the restricted age range in our participants, spanning 26–46 months, reduced the number of age effects in the omnibus tests. Longitudinal analysis using AFQ will clarify patterns in tract maturation with a new level of detail.

Laterality in diffusion parameters

Similar to sexual dimorphism, asymmetry in white-matter diffusion parameters is region specific and age-dependent (Ardekani et al., 2007; Bonekamp et al., 2007; Hasan et al., 2010; Liu et al., 2010; Trivedi et al., 2009). Studies in very young children suggest left-ward asymmetries with higher fractional anisotropy in the left corticospinal tract, left superior longitudinal fasciculus, left arcuate fasciculus and possibly the left thalamic radiations (Dubois et al., 2009; Liu et al., 2010). Lifespan development reports (mostly starting above age 5) also suggest a mild left-ward asymmetry in overall FA but with few significant comparisons among specific tracts (Lebel et al., 2012; Trivedi et al., 2009). We found diffusion parameter asymmetries in 9 of the 10 tract pairs/sides

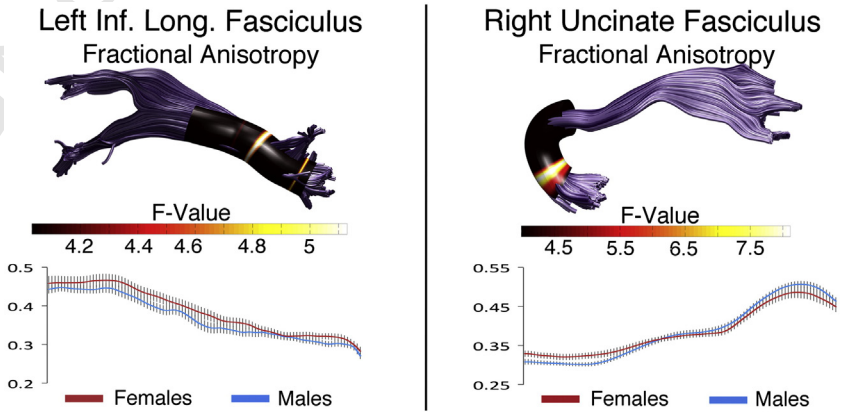

Fig. 5. Sex differences in the left superior longitudinal fasciculus and right uncinate fasciculus. Tract profiles illustrating sex differences in FA along the left ILF and right uncinate in typically developing male and female children. Color bar indicates F statistic values from Bonferroni-corrected analyses of covariance conducted at each location along the tracts length. Significant comparisons are indicated by non-black regions. Corresponding plots for FA in males and females are presented below each tract profile.

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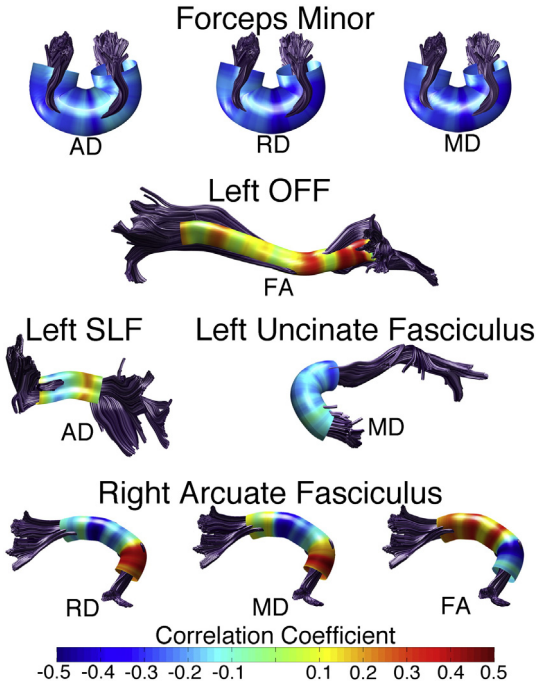

Fig. 6. Relationship between participant age and diffusion parameters in several tracts. Tract profiles illustrating partial correlations between age and various diffusion parameters in tracts where age emerged as a significant covariate. Scanner type and handedness are controlled. Correlation strength was variable along the tract. Colors represent the strength of the relationship as indicated by r-values. Warmer colors indicate a positive relationship and cooler colors indicate a negative one.

examined (Fig. 2, Table 3). Several of these asymmetries have been reported in adults (Bonekamp et al., 2007; Büchel et al., 2004; Thiebaut de Schotten et al., 2011; Westerhausen et al., 2007) and leftward asymmetries in the arcuate fasciculus and cingulum are especially prevalent.

Mean FA and tract density are greater in the left arcuate fasciculus compared with the right in adults and older children (Büchel et al., 2004; Dubois et al., 2009; Fletcher et al., 2010; Lebel and Beaulieu, 2009; Paus et al., 1999; Powell et al., 2006; Rodrigo et al., 2007). We also observed asymmetry of arcuate FA in younger children (Fig. 2). In agreement with Fletcher et al.'s (2010) description in typically developing adolescent boys, we also found higher MD and RD in the right arcuate compared with the left (Table 3). Asymmetry in the arcuate fasciculi is linked to faster maturation in the left arcuate due to the important role it plays in that hemisphere's language circuit (Klingberg et al., 2000; Rauschecker et al., 2009; Rolheiser et al., 2011; Yeatman et al., 2011).

A second consistent asymmetry is a leftward bias in cingulum FA which is robust and present over the lifespan (Bonekamp et al., 2007; Gong et al., 2005a, 2005b; Trivedi et al., 2009; Wilde et al., 2009). We confirmed higher mean FA in the left cingulum of children and show that this is the product of higher AD in the left cingulum and higher RD in the right cingulum (Fig. 2). The greater AD in the left and greater RD in the right cingulum suggest a more cohesive tract bundle with possibly greater axonal density and myelination in the left hemisphere.

Several of the cingulum's gray matter targets such as the cingulate cortex and amygdala also exhibit considerable laterality (Andersen and Teicher, 1999; Cooke et al., 2007; Gasbarri et al., 2007; Giedd et al., 1997; Huster et al., 2007; Johnson et al., 2008; Killgore et al., 2001; Paus et al., 1996; Scicli et al., 2004; Yücel et al., 2001), and laterality in anterior cingulate gray matter has been linked to personality, executive-control, and risk for psychotic illness (Fornito et al., 2004; Pujol et al., 2002; Yücel et al., 2003). The current data illustrate that the cingulum, which receives contributions from both the amygdala and cingulate cortex, is also asymmetric from a young age in humans.

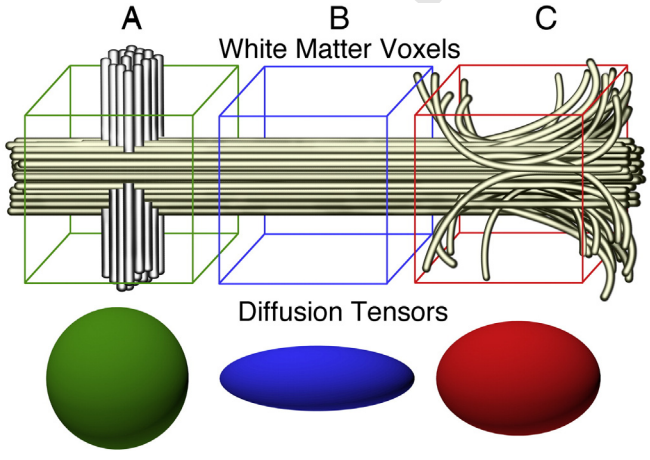

Fig. 7. Environmental contributions to tract anisotropy. Variations in diffusion parameters along tracts during normative development are likely a combination of tract specific (myelin content, axonal integrity) and local environment contributions. Voxel A contains a tract of interest (yellow) as well as a crossing tract (gray), resulting in low anisotropy measurements at this point. Voxel B contains only the tract of interest and exhibits high anisotropy. Within voxel C axons from nearby gray matter join the tract and some axons break off heading towards gray matter targets. The result would be a drop in anisotropy measurements at this point in the tract.

Limitations

The current study provides a new level of detail regarding white matter diffusion parameters in young children, but there are a few issues to note. Although AFQ provides a method to assess within tract variance, the use of a tensor models means that we do not trace the trajectory of fiber tracts crossing the principle tract bundle in a voxel. This means that we measure the core of a tract but do not measure all of its smaller branches. Relatedly, diffusion parameters were not measured at the extremes of each tract near the cortical endpoints. Measuring in these areas may provide useful information but will likely also be subject to extremely high levels of variability due to partial voluming with gray matter. Additionally, because AFQ tracts fibers in native space, due to individual variability in factors such as tract curvature, tract size, and image quality, some tracts entered statistical analysis with a greater sample size than others (Table 2). Additional analysis of the right cingulum and right arcuate, the only tracts with fewer than 50 subjects might identify additional within or between subjects effects in these tracts. Finally, because the current data are part of a larger longitudinal study taking place over several years, improvements to the research center's scanner software occurred during data collection. To account for this, we have included scanner status as a covariate in our analyses. While there were differences in fiber identification rates (Table 2) the between-subjects factor in our model (participant sex) was not differentially distributed among the two scanner statuses (Fisher's exact test, $p = 0.62$).

Conclusions

Our results indicate that in young children, factors such as within-tract variability, sex, hemisphere and age exhibit variable influence on diffusion parameters along the major fasciculi. These findings also illustrate how repeated sampling of multiple diffusion parameters produces a more detailed understanding of a tract than mean measures of a single descriptor such as fractional anisotropy and mean diffusivity. Normal variation in tract diffusion parameters can be caused by gross properties such as tract curvature and partial voluming with nearby structures but may also illustrate changes in local myelination, axonal density and/or the addition and elimination of axons to the tract. Given the highly variable patterns of correlation between age and diffusion parameters

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along the tract length, longitudinal studies describing changes to the diffusion parameter profile of a tract are particularly informative.

The present study provides an enhanced level of detail regarding sexual dimorphism and hemispheric asymmetry in tract diffusion properties. Abnormal cerebral asymmetry has been linked to intellectual deficits and schizophrenia (Burns et al., 2003; Crow, 2004; Rosenberger and Hier, 1980; Wang et al., 2004) and disorders such as autism and depression exhibit pronounced sex biases in the population. A more thorough understanding of how sexual dimorphism and hemispheric asymmetry influence major fasciculi in normative development may improve our ability to identify white matter abnormalities in several disorders.

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