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ORIGINAL RESEARCH

Altered brain structures in the dorsal and ventral language pathways in individuals with and without developmental language disorder (DLD)

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Abstract
Developmental Language Disorder (DLD) is a neurodevelopmental disorder characterized by difficulty learning and using language, and this difficulty cannot be attributed to other developmental conditions. The aim of the current study was to examine structural differences in dorsal and ventral language pathways between adolescents and young adults with and without DLD (age range: 14–27 years) using anatomical magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI). Results showed age-related structural brain differences in both dorsal and ventral pathways in individuals with DLD. These findings provide evidence for neuroanatomical correlates of persistent language deficits in adolescents/young adults with DLD, and further suggest that this brain-language relationship in DLD is better characterized by taking account the dynamic course of the disorder along development.

Keywords Developmental language disorder · Dorsal pathway · Ventral pathway · Structural brain imaging

Introduction

Developmental language disorder (DLD) is a neurodevelopmental disorder characterized by difficulty learning and using language, and this difficulty cannot be attributed to sensory, intellectual, social, or emotional problems (Leonard 1998). Epidemiological studies have shown that DLD affects approximately 7% of children starting school (Norbury et al. 2016; Tomblin et al. 1997). Morphosyntactic deficits are the primary hallmark of DLD. Children with DLD have significant problems with production and/or comprehension of grammatical inflections and complex sentences, and these deficits persist well into adolescence and adulthood (Norbury et al. 2008). While most earlier work focused on development of morphology and syntax in DLD, recent studies have shown that individuals with DLD also have atypical lexical-semantic development, which frequently manifests as a small quantity of words learned as well as a poor quality of words learned (see Nation 2014, for a review).

Despite its high prevalence rate, the neurobiology of DLD remains poorly understood (Krishnan et al. 2016). Understanding the neural basis of DLD is important, both theoretically and clinically. On the one hand, DLD represents the lower end of the normal distribution with regard to language ability (Dollaghan 2011; Leonard 2014), and thus findings concerning the neurobiological basis of DLD will shed light on the mechanisms underlying individual differences in language development and learning. On the other hand, better understanding of the neural correlates of DLD will provide knowledge on the potential causes of language learning difficulties, which, in turn, will inform effective clinical interventions.

The dual-stream model of language

Understanding the neurobiology of language has been an enduring problem in neuroscience. During the past decade, growing evidence supports a dual-stream model of language, wherein two anatomically and functionally distinct pathways work together to facilitate language learning and processing

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(e.g., Dick et al. 2014; Friederici 2009; Friederici and Gierhan 2013; Hickok and Poeppel 2004; Saur et al. 2008). Despite some variations in details of each proposal, a general consensus has emerged that the dorsal pathway supports auditory-to-motor integration by mapping acoustic speech sounds to articulatory representations, while the ventral pathway supports lexical-semantic processing, mapping sound-based representations of speech to widely distributed conceptual representations. These two language pathways have different specialties in terms of anatomical projections and function, and a successful execution of language behavior requires complex collaboration and integration of processing between them (Cloutman 2013; Rolheiser et al. 2011).

The dorsal pathway

The dorsal pathway connects the temporal cortex with the frontal cortex via the white matter tracts of the arcuate fasciculus (AF) and superior longitudinal fasciculus (SLF) (Catani et al. 2005; Glasser and Rilling 2008). The prominent language-relevant regions in the dorsal pathway include the *pars opercularis* (BA44) of the inferior frontal gyrus (IFG), the transverse temporal gyrus (TTG),[1] the superior temporal gyrus (STG), *planum temporale*, and the supramarginal gyrus (SMG). Brain imaging studies have suggested that most components of the AF/SLF tracts reach maturation during late adolescence, and the frontal portion of the AF/SLF continues to mature in early adulthood (Asato et al. 2010; Lebel et al. 2012; Simmonds et al. 2014).

A prominent function of the dorsal pathway is auditory-to-motor mapping (Hickok and Poeppel 2004; Liégeois et al. 2019; Saur et al. 2008). This function is associated with the structural connection between the temporal cortex and the premotor cortex, which facilitates the translation of auditory representations of speech signals into articulatory/motor representations. Brain imaging studies showed that this part of the dorsal pathway was detectable in newborns (i.e., the fiber tract could be delineated in diffusion-weighted imaging (DWI) data by tractography), and was strongly activated as a function of speech input (Brauer et al. 2013; Leroy et al. 2011; Perani et al. 2011). These findings suggest that the dorsal pathway connecting the temporal cortex with the premotor cortex is sensitive to speech sounds early on, providing a possible neurobiological basis for the tuning process as the native phonology develops.

Recently, researchers proposed that the dorsal connection between the temporal cortex and the *pars opercularis* (BA44) of the IFG is relevant for more complex linguistic function, such as processing of syntactically complex sentences (Brauer et al. 2013; Friederici 2009; Perani et al. 2011; Wilson et al. 2011). DWI data showed that unlike the dorsal connection between the temporal cortex and the premotor cortex, this part of the dorsal pathway was not detectable in infants, but was able to be delineated in the brains of 7-year-olds and above (Brauer et al. 2013). This finding is consistent with behavioral studies showing late acquisition of syntactically complex sentences in children.

The ventral pathway

The ventral pathway consists of several fiber bundles, including 1) the inferior fronto-occipital fasciculus (IFOF) that connects the frontal cortex with the posterior temporal cortex, the occipital cortex, and the parietal cortex, 2) the inferior longitudinal fasciculus (ILF) that connects the temporal pole, hippocampal formation, and the inferior temporal gyrus to most of the occipital cortex, and 3) the uncinate fasciculus (UF) that connects the superior aspect of the temporal pole to the basal and lateral portions of the frontal cortex (Bajada et al. 2015; Dick et al. 2014; Duffau et al. 2013; Friederici 2009; Saur et al. 2008). The prominent language-relevant regions in the ventral pathway include the inferior temporal gyrus (ITG), the middle temporal gyrus (MTG), the temporal pole, and the *pars triangularis* and the *pars orbitalis* of the IFG.

Researchers have successfully delineated the ventral pathway in newborns (Brauer et al. 2013; Perani et al. 2011). Lifespan DWI studies showed that the IFOF and the ILF tracts reached maturation in young adulthood, whereas the UF was one of the latest maturing tracts in the brain, with development continuing in the third decade of life (Asato et al. 2010; Lebel et al. 2012; Simmonds et al. 2014).

In terms of the function of the ventral pathway, it is generally agreed that the ventral pathway is associated with lexical-semantic processing, serving as a sound-to-meaning interface by mapping auditory representations to widely distributed semantic representations (Duffau et al. 2013; Hickok and Poeppel 2004; Friederici and Gierhan 2013; Saur et al. 2008; Wong et al. 2011). However, the unique contribution of each fiber tract to lexical-semantic processing remains poorly understood. Brauer et al. (2011) proposed that the initial prominence of the ventral pathway may also play a compensatory role in supporting syntactic processing in young children when the dorsal connection between the temporal cortex and the IFG is not sufficient due to its immaturity.

Brain research on DLD

Despite growing evidence for the neurobiology of language development, there is a paucity of research on brain structure and/or function in DLD, not to mention age-related differences in the brain. Much of the earlier work centered on

[1] The TTG is part of both dorsal and ventral pathways. For the purpose of simplicity, we categorize it as one of the ROIs in the dorsal pathway. It is because the primary function of the TTG is speech processing (e.g., processing spectral properties of sounds), which is a major function of the dorsal pathway.

whether individuals with DLD have atypical structural asymmetry in language-relevant regions. The presumption of these studies is that if a lateralized brain facilitates language development and learning, then a disruption of the normal pattern of left-hemisphere language lateralization could be a cause of poor language development, as shown in individuals with DLD. The results in general showed reversal of asymmetry in multiple language-relevant brain regions in individuals with DLD, including the *planum temporale* and the IFG (Cohen et al. 1989; De Fossé et al. 2004; Gauger et al. 1997; Herbert et al. 2005; Jernigan et al. 1991; Plante et al. 1991). However, Bishop (2013) challenged this popular view of DLD as a result of a poorly lateralized brain. Using genetic data to support her arguments, Bishop suggested that atypical cerebral asymmetry may act as a separate risk factor for DLD, or alternatively, be a consequence of DLD.

In addition to earlier work on cerebral asymmetry, recent studies showed abnormal structure and function of language-relevant regions in DLD. For example, functional MRI studies showed reduced brain activations within the frontal, temporal, and parietal areas in individuals with DLD during language tasks (Badcock et al. 2012; De Guibert et al. 2011; Hugdahl et al. 2004). In terms of structural brain imaging findings, individuals with DLD (age range: 8 to 30 years across different studies) revealed abnormal morphology and volumes of several language-relevant brain regions, including the IFG, the *planum temporale*, and the STG (Badcock et al. 2012; Clark and Plante 1998; Gauger et al. 1997; Herbert et al. 2003; Jancke et al. 2007; Jernigan et al. 1991; Kurth et al. 2018; Leonard et al. 2002). However, findings pertaining to the direction of volumetric difference (i.e., smaller vs. larger volumes in the brain regions of interest in DLD) were inconsistent across studies, and this difference may be, at least partially, attributed to whether the whole brain measures (e.g., intracranial volumes) were controlled, or how they were controlled.

A dearth of research focuses on language-relevant white matter fiber tracts in the DLD population. Only five diffusion tensor imaging (DTI) studies have been conducted to examine the AF/SLF tracts in the dorsal pathway in children with and without DLD (Morgan et al. 2018; Roberts et al. 2014; Verhoeven et al. 2012; Verly et al. 2018; Vydrova et al. 2015), and two of them included the IFOF, ILF, UF in the ventral pathway as well (Verly et al. 2018; Vydrova et al. 2015). Most findings (but see Morgan et al. 2018) suggest deficient structural connectivity of both dorsal and ventral pathways in children with DLD. It remains unclear whether group differences occur in adolescence and early adulthood, and vary across age.

To sum up, there have been growing attempts to study the neurobiology of DLD in the past decades. However, results remain inconsistent due to varying methods, small sample size, heterogeneity of subjects with DLD, as well as sample limitation (e.g., postmortem case study (Cohen et al. 1989), or recruitment of male subjects only (De Fossé et al. 2004)). Moreover, DLD is a *neurodevelopmental* disorder, and thus neuroanatomical differences might look different across age if DLD is considered in a developmental context. At the phenotypic level, substantial evidence has shown a dynamic nature of DLD, suggesting a continuous interaction between the language environment and learning capabilities of a child (Evans 2001; Poll 2011; Thomas and Karmiloff-Smith 2002). Soriano-Mas et al. (2009) showed global increases in gray and white matter volumes in the brains of children with DLD, as well as regional gray matter increases in the right perisylvian region and in the occipital petalia. Of particular interest was the fact that in older children (over 11 years of age) these brain differences were not significant between the DLD and non-DLD group. It should be noted that intracranial volumes (ICV) were not corrected for volumetric analysis in the study, and thus results might be reversed after adjusting for ICV. Nevertheless, Soriano-Mas et al.' work confirms the dynamic nature of DLD, and highlights the necessity to take account of age in evaluating the neuroanatomical basis of DLD.

The current study

The aim of the current study was to examine structural differences in dorsal and ventral language pathways between adolescents and young adults with and without DLD. We aimed to address the limitations in previous studies by 1) increasing the sample size, 2) recruiting participants via school-wide screening of language ability in order to reduce sampling bias, and 3) expanding the age range of participants to examine whether group differences varied between the ages of 14 and 27 (i.e., adolescence and young adulthood). The regions of interest (ROIs) included: 1) the gray matter volumes of language-relevant brain regions in the dorsal and ventral pathways, and 2) the white matter microstructure of the fiber tracts in the two pathways. We hypothesized that individuals with DLD would show poorer development of both dorsal and ventral language pathways across the study age range than the comparison participants, given that they have persistent language learning difficulty in multiple domains of language (e.g., phonology, syntax, semantics) in adolescence and adulthood (Leonard 1998).

Methods

Participants

Subjects were recruited from two sources targeting different age groups. None of the subjects reported having other neurodevelopmental disorders (e.g., intellectual disabilities,

autism spectrum disorders) or hearing loss. Table 1 summarizes the demographic information and test scores of all subjects. While the prevalence rate for males with DLD was relatively higher than those for females with DLD (Tomblin et al. 1997), females in general are more willing to participate in research studies than males (Markanday et al. 2013), which explains why we had more female subjects with DLD than male subjects with DLD in the current study.

Cohort 1

The first cohort of subjects was drawn from the Iowa Longitudinal Study (Tomblin 2008; DLD: $n = 14$, Comparison: $n = 12$). These participants were originally assessed in kindergarten and validated as having either typical language development or DLD using diagnostic standards and measurement tools (Tomblin et al. 1996). At the point of testing, they were within the age range of 19 to 27 years old, having either typical language functioning or persistent language difficulty as shown in our longitudinal database. To reconfirm their diagnosis at the time of testing, all participants were tested on two nonverbal IQ measures and three language tasks. The two nonverbal IQ measures were the Block Design and Matrix Reasoning subtests from Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler 1999). The three language tasks included: 1) Word Derivations, a subtest from The Test of Adolescent and Adult Language, Fourth Edition (TOAL-4; Hammill et al. 2007), 2) Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4; Dunn and Dunn 2007), and 3) a modified version of the Token Task (De Renzi and Faglioni 1978; Morice and McNicol 1985). Language composite scores were obtained by averaging the standard scores of three language measures. Subjects in the DLD group must have a persistent diagnosis of DLD shown in our longitudinal database, as well as having the current language composite scores below one standard deviation (SD) below the mean. Subcortical volumes (i.e., the basal ganglia and the hippocampus) of 12 subjects with DLD and 12 subjects with typical language ability in Cohort 1 have been reported elsewhere (Lee et al. 2013).

Cohort 2

The second cohort of subjects was recruited from several high schools and colleges in Eastern Iowa (DLD: $n = 19$; Comparison: $n = 61$). The age range was between 14 and 20 years old. The recruitment method was different from the one used in the first cohort. Instead of recruiting subjects from our longitudinal study, we recruited the second cohort via school-wide screening of language ability in order to reduce sampling bias. Adolescents were then drawn from the screened pool to provide a sample that had a roughly rectangular distribution, with oversampling of adolescents in the high and low ends of the normal distribution with regard to language. By doing so, results would be able to shed light on the biological mechanisms underlying individual differences in language.

The diagnosis of DLD was based on five language tests and the nonverbal IQ subtests of the WASI (Wechsler 1999). The five language tests used in the diagnosis included: 1) PPVT-4 (Dunn and Dunn 2007) to assess receptive vocabulary, 2) Expressive Vocabulary Test, Second Edition (EVT-2; Williams 1997) to assess expressive vocabulary, 3) Recalling Sentences in Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF-4; Semel et al. 2003) to assess the ability to recall and reproduce sentences of syntactic complexity, 4) Understanding Spoken Paragraphs in CELF-4 to assess passage comprehension, and 5) Word Derivations in the TOAL-4 (Hammill et al. 2007) to assess knowledge of derivational morphology. Language composite scores were then

Table 1 Summary of demographics and test scores for participants with and without developmental language disorder (DLD) in each cohort

Cohort 1	**Comparison (n = 12)**		**DLD (n = 14)**		
	M	*SD*	M	*SD*	*p*
Age (year)	22.10	.51	22.42	2.02	.53
Sex (Male:Female)	4:8		5:9		.90
Handedness (Right:Left)	12:0		13:1		.35
Language composite scores	100.05	11.85	68.51	16.00	<.001
Nonverbal IQ	112.50	10.03	89.36	13.40	<.001
Cohort 2	**Comparison (n = 61)**		**DLD (n = 19)**		
	M	*SD*	M	*SD*	*p*
Age (year)	16.62	1.40	16.96	1.49	.36
Sex (Male:Female)	25:36		8:11		.93
Handedness (Right:Left)	55:6		13:6		.02
Language composite scores	102.09	9.54	78.47	5.15	<.001
Nonverbal IQ	100.46	14.56	84.16	9.58	<.001

obtained by averaging the standard scores of all language measures. Individuals with DLD must have their language composite scores below one SD below the mean.

Establishing comparability of language measures used in two cohorts

Given the two-year gap between the two phases of subject recruitment, different recruitment methods, as well as different ages of subjects, the measurement of subject's language ability requires use of different tasks. In these cases, it is assumed that different measures we chose are reflective of a common latent trait. Several studies have shown that oral language in childhood and adolescence consists largely of a unidimensional latent trait (Anthony et al. 2014; Bornstein et al. 2014; Language and Reading Research Consortium 2015; Tomblin and Zhang 2006). Therefore, we can expect that different manifest measures in this study are reflective of the same latent language ability trait. To test this prediction, we examined the correlation of the tests in common across the cohorts (i.e., PPVT and Word Derivations in TOAL-4) with the tests that were unique in each cohort. The results showed that the common measures were strongly correlated with the unique measures employed for Cohort 1, $r = .60$, $p = .001$, and for Cohort 2, $r = .81$, $p < .001$. The Fisher's r-to-z transformation showed that these two correlations were not significantly different, $z = -1.9$, $p = .06$, suggesting that language measures used in different cohorts were indeed reflective of the same latent language ability trait. Thus, groups were comparable between the two cohorts with regard to language status (i.e., DLD or Comparison).

The study was approved by the institutional review board (IRB) at the University of Iowa. All participants provided consent in accord with the Declaration of Helsinki after being informed of the study procedures and purpose.

MRI acquisition

All image scans were obtained at the University Hospital and Clinics of Iowa using the Siemens 3 T Trio scanner. Subjects underwent an imaging protocol that collects high-resolution anatomical images and a diffusion tensor sequence.

Anatomical image

The high-resolution anatomical images consisted of a T1 weighted volume and also proton density (PD/T2) images collected with a dual echo fast spin-echo two-dimensional (2D) sequence. The T1 weighted images were acquired in the coronal plane using a 3D MP-RAGE sequence with the following parameters: echo time (TE) = 2.86 ms, repetition time (TR) = 2300 ms, inversion time = 900 ms, flip angle = 10°, number of excitations (NEX) = 1, field of view (FOV) = 256 × 256 × 256 mm, and slice thickness = 1 mm. The PD/T2 weighted images were acquired with the following parameters: TE = 430 ms, TR = 4800 ms, NEX = 1, slice thickness = 1.4 mm, FOV = 256 × 256 × 256 mm, and turbo factor = 137. The total time of image acquisition was approximately 21 min.

Diffusion-weighted image

The diffusion-weighted images were collected using a 2D twice refocused echo-planar spin-echo sequence with the following parameters: TE = 81 ms, TR = 9000 ms, FOV = 256 × 256 mm, Matrix = 128 × 128, slice thickness = 2.0 mm, the number of diffusion directions = 64, and b-values = 1000 s/mm^2. The total time of image acquisition was approximately 10 min.

Image preprocessing and processing

Anatomical image processing

The anatomical data were preprocessed using AutoWorkup, an automated procedure implemented in the software package Brain Research: Analysis of Images, Networks, and Systems (BRAINS; Magnotta et al. 2002). The steps of the standard pipeline included: 1) anterior commissure (AC)-posterior commissure (PC) alignment of T1 volume, 2) co-registration of T2-weighted images to AC-PC aligned T1, defining of Talairach parameters to warp the Talairach grid onto the raw space of each subject, 3) tissue classification of white matter, gray matter, and cerebrospinal fluid (Harris et al. 1999), and 4) skull stripping using an artificial neural network (Magnotta et al. 1999). After completion of AutoWorkup, all scans were individually inspected for quality control. The brains were then parcellated into functional regions using FreeSurfer (Dale et al. 1999; Fischl et al. 1999, 2001). Cortical gray matter volumes reported in the current study were extracted for ROIs from each subject's brain image in its native space. Figure 1 showed the ROIs, including STG, TTG, *pars opercularis*, and SMG in the dorsal pathway, and ITG, MTG, *pars triangularis*, *pars orbitalis*, and temporal pole in the ventral pathway.

Diffusion-weighted image processing

The DTIPrep software (Liu et al. 2010) was used to perform several quality assurance steps as well as removing volumes within a scan that did not meet its minimal quality criteria before tensor image estimation. The automatic pipeline in the software includes: 1) protocol verification, 2) slice-wise checking, and 3) detection and removal of artifacts caused by eddy-currents, head motion, bed vibration and pulsation, venetian blind artifacts, as well as intensity inconsistencies

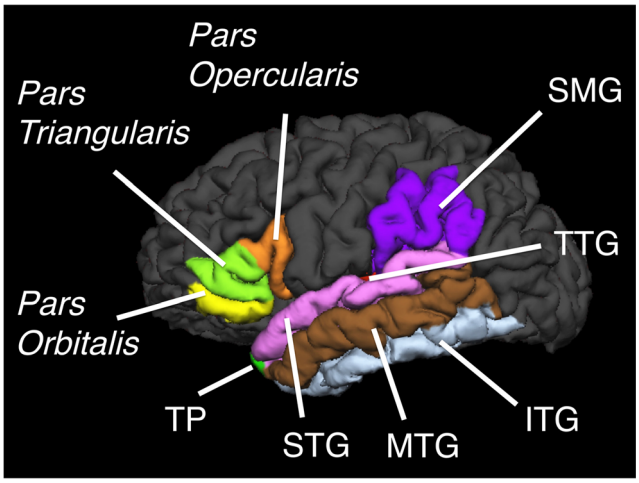

Fig. 1 FreeSurfer map of the regions of interest in the left hemisphere. The transverse temporal gyrus (TTG) is buried within the lateral sulcus. ITG: Inferior temporal gyrus; MTG: Middle temporal gyrus; SMG: Supramarginal gyrus; STG: Superior temporal gyrus; TP: Temporal Pole; TTG: Transverse temporal gyrus.

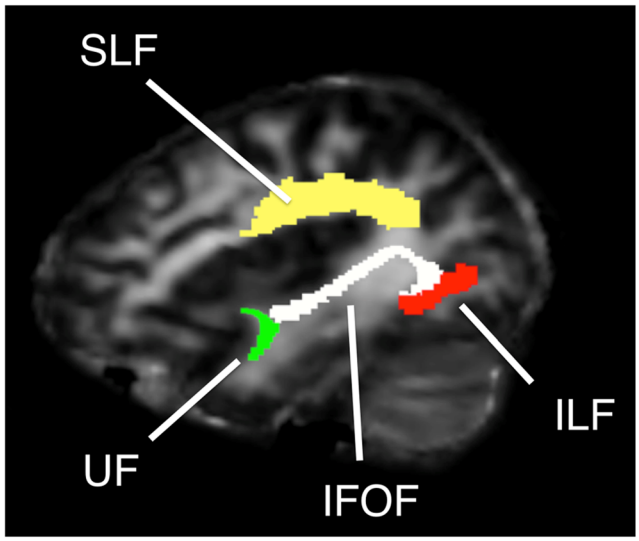

Fig. 2 JHU white matter tractography atlas of the regions of interest. IFOF: Inferior fronto-occipital fasciculus; ILF: Inferior longitudinal fasciculus; SLF: Superior longitudinal fasciculus; UF: Uncinate fasciculus.

(Oguz et al. 2014). The final dataset contained an averaged baseline image and diffusion-weighted images that passed all the quality assurance tests. Next, we used the Guided Tensor Restore Anatomical Connectivity Tractography (GTRACT; Cheng et al. 2006) software to process the output files from the DTIPrep, including estimation of tensor images and subsequent computation of fractional anisotropy. Johns Hopkins University (JHU) white matter tractography atlas was then used to label white matter fiber tracts of interest, including the SLF (connections between the frontal, parietal, occipital, and temporal lobes), IFOF (connections between the frontal lobe and the occipital lobe), UF (connections between the frontorbital cortex and the anterior temporal lobe), and ILF (connections between temporal lobe and the occipital lobe) (see Hua et al. 2008; Wakana et al. 2007, for details). In JHU atlas, SLF and AF are not delineated separately. Figure 2 shows the fiber tracts of interest.

Statistical analysis

Statistical analyses were carried out using SPSS version 25. Brain measures more than two SDs away from the mean were considered as outliers and thus removed from the dataset for the purpose of normalization. False discovery rate (FDR) was used to correct for multiple comparisons (Benjamini and Hochberg 1995). In all analyses, sex, handedness, cohort, and nonverbal IQ were controlled as covariates. It should be noted that we did not aim to contrast the two cohorts; instead, we treated them as one sample that spans adolescence into adulthood. To be conservative, we created a dummy variable for cohort (i.e., Cohort 1 and 2), and entered it in the model as a covariate to control for the potential cohort effect.

We had one participant with DLD from the longitudinal database who was older (27 years) than the rest of the participants (14 to 24 years). To explore whether including this participant skewed the results, we ran all the analyses without him/her, and findings were not materially different. Thus, we did not remove the participant from our datasets. We also want to point out that generally speaking, it is less optimal to include subjects with left handedness. However, the relationship between handedness and DLD remains unclear. Bishop (2013) showed that while there seems no genetic links between handedness and speech/language difficulties, the high comorbidity may reflect delayed neuromotor maturation. Thus, excluding participants with DLD who are left handed may create a sampling bias. It is noted that the direction of results remained the same when excluding participants with left handedness.

Volumetric analysis

There was a significant difference in the intracranial volume (ICV) between the DLD group (M = 1284.71, SD = 152.12) and the comparison group (M = 1396.32, SD = 157.28) after controlling for age, sex, handedness, cohort, and nonverbal IQ, $F(1, 99) = 11.04$ $p = .001$, $\eta_p^2 = .10$. Thus, we transformed absolute volumes into relative volumes to avoid potential confounding effects. Relative volumes were obtained by dividing absolute volumes by ICV and then multiplying by 100. Analysis of variance (ANOVA) was performed to assess age-by-group interaction effects on relative gray matter volumes of each ROI.

Analysis of diffusivity measures

Fractional anisotropy (FA) was chosen as the diffusion measure. FA is a measure of the degree of diffusion directionality, and is the most commonly reported index in diffusion imaging to reflect the microstructure of the brain anatomy (Alexander et al. 2007). Developmental research has shown that maturation of white matter over this age range can be reflected by an increase of FA (Huppi and Dubois 2006; Qiu et al. 2015). To examine age-related changes in white matter microstructures of the ROIs between individuals with and without DLD, the ANOVA was carried out to examine age-by-group interaction effects on FA values in the ROIs.

In addition to the ROIs, the corpus callosum fiber tracts (i.e., the genu, the body, and the splenium of the corpus callosum) were chosen as the control fiber tracts in order to ensure that any diffusivity differences observed were not significantly attributed to global microstructural alterations. The corpus callosum forms the largest commissural white matter bundle in the brain, playing a vital role in the integration of information between left and right cerebral hemispheres (Hofer and Frahm 2006). Previous brain imaging studies did not show significant difference in the corpus callosum between individuals with and without DLD (Herbert et al. 2004; Preis et al. 2000).

Results

Volumetric analysis

Table 2 summarizes the absolute and relative volumes of the ROIs in both groups[2] (see Fig. 3a, b for mean relative volumes of the ROIs in each group).

Table 3 provides the results for Group and Age effects and their interactions for the relative volumes in each ROI. In the upper panel, the ROIs comprising the dorsal pathway are shown. In terms of the Group main effect, the DLD group had significantly larger relative volumes of the left TTG in the dorsal pathway than the comparison group, $F(1, 95) = 6.48$, $p = .01$, $\eta_p^2 = .07$. None of the other ROIs in the dorsal pathway showed significant Age or Group effects.

The ROIs comprising the ventral pathway showed significantly larger volumes for the DLD of the right *pars orbitalis*, $F(1, 95) = 7.16$, $p < .01$, $\eta_p^2 = .07$, of the right temporal pole, $F(1, 95) = 9.17$, $p < .01$, $\eta_p^2 = .09$, and the left temporal pole, $F(1, 95) = 11.11$, $p < .01$, $\eta_p^2 = .11$, in the DLD group. Additionally, significant increases in relative volumes were seen across age for the left MTG, $F(1, 95) = 6.23$, $p = .01$, and for the left *pars triagularis*, $F(1,95) = 6.64$, $p = .01$.

FA analysis

Participants whose diffusion images did not pass the rigorous quality control performed by DTIPrep (Liu et al. 2010) were excluded from further analyses (Comparison: $n = 12$, DLD: $n = 2$). Table 4 provides the summary statistics for the FA values for the tracts of interest in the two groups.

Results of tests for the effects of Group, Age and their interactions of the FA in the tracts comprising the dorsal pathway are shown in Table 5. Significantly reduced FA in the DLD group compared with the comparison group was found in the left SLF, $F(1, 86) = 6.78$, $p = .01$, $\eta_p^2 = .07$, and in the right SLF, $F(1, 86) = 5.96$, $p = .02$, $\eta_p^2 = .07$. In addition, there was a significant Age-by-Group interaction effect on the right SLF, $F(1, 86) = 10.71$, $p < .001$, $\eta_p^2 = .11$. Follow-up tests showed that the DLD group did not show significantly increased FA in the right SLF across age, $r = -.25$, $p = .20$, whereas the comparison group did, $r = .39$, $p = .002$ (see Fig. 4). The pattern of increased FA across age in the comparison group is consistent with previous DTI studies showing an increase in FA with development in healthy children (Barnea-Goraly et al. 2005; Huppi and Dubois 2006; Kochunov et al. 2012).

Regarding the fiber tracts in the ventral pathway, significantly reduced FA values were found in the DLD group for the left IFOF, $F(1, 86) = 5.70$, $p = .02$, $\eta_p^2 = .06$, the right IFOF, $F(1, 86) = 9.71$, $p < .01$, $\eta_p^2 = .10$, and the left UF, $F(1, 86) = 9.05$, $p = .01$, $\eta_p^2 = .10$, with no significant Age or Age-by-Group interactions. Two tracts within the ventral pathway showed significant Age-by-Group interaction effects, namely the left ILF, $F(1, 86) = 5.41$, $p = .02$, $\eta_p^2 = .06$, and the right UF, $F(1, 86) = 8.52$, $p = .004$, $\eta_p^2 = .09$. Follow-up tests showed that the DLD group had no significantly increased FA across age in the left ILF, $r = .20$, $p = .06$, or in the right UF, $r = .06$, $p = .56$. In contrast, the comparison group showed a significantly increased FA across age in the left ILF, $r = .43$, $p = .001$, as well as in the right UF, $r = .30$, $p = .019$ (see Figs. 5 and 6).

Descriptive statistics regarding the FA values for the control tracts are also shown in Table 4. No significant Age, Group or Age-by-Group interaction effects were found for any of these control tracts (see Table 5). In other words, significant difference in the ROIs as shown above could not be solely accounted for by global white matter immaturity.

Discussion

In the current study, we examined the brain structures as well as the association fiber tracts in the dorsal and ventral language pathways in individuals with and without DLD. We showed age-related structural brain differences in both dorsal

[2] Absolute volumes were provided in order that the current findings could be compared to those that were not corrected for ICV. Our statistical analyses were limited to the relative values.

Table 2 Summary of absolute and relative gray matter volumes of the regions of interest (ROI).

ROIs		Group	Absolute volumes		Relative volumes	
			Mean	*SD*	Mean	*SD*
Dorsal pathway						
Superior temporal gyrus (STG)	R	Comparison	13,242.79	1565.52	9.59	.86
		DLD	12,098.70	1603.45	9.69	.73
	L	Comparison	13,858.76	1621.03	10.00	.90
		DLD	12,346.42	1836.968	9.81	.84
Transverse temporal gyrus (TTG)	R	Comparison	1010.76	158.74	.72	.09
		DLD	970.36	177.53	.75	.09
	L	Comparison	1305.24	211.24	.94	.14
		DLD	1236.63	171.92	.96	.10
Supramarginal gyrus (SMG)	R	Comparison	12,122.80	1741.97	8.66	.97
		DLD	11,212.48	1535.05	8.47	1.00
	L	Comparison	12,975.97	1878.54	9.30	1.09
		DLD	11,625.90	1939.72	9.08	.83
Pars Opercularis	R	Comparison	4622.06	763.98	3.32	.45
		DLD	4461.16	607.86	3.56	.48
	L	Comparison	5673.87	794.09	4.18	.55
		DLD	5244.91	894.83	4.09	.45
Ventral pathway						
Inferior temporal gyrus (ITG)	R	Comparison	11,827.17	1767.16	8.53	.93
		DLD	10,772.63	1752.41	8.55	1.07
	L	Comparison	12,174.93	1785.98	8.76	1.01
		DLD	11,012.10	1755.04	8.82	1.19
Middle temporal gyrus (MTG)	R	Comparison	14,029.86	2011.80	10.06	.88
		DLD	13,312.50	2100.44	10.35	.81
	L	Comparison	13,015.71	1880.45	9.39	.85
		DLD	11,279.06	1977.04	8.97	1.06
Pars Orbitalis	R	Comparison	3097.74	416.85	2.22	.31
		DLD	2923.66	441.47	2.28	.29
	L	Comparison	2526.91	351.83	1.82	.22
		DLD	2294.58	349.42	1.80	.25
Pars Triangularis	R	Comparison	4856.68	847.58	3.53	.64
		DLD	4517.00	745.16	3.57	.53
	L	Comparison	4300.93	635.44	3.02	.40
		DLD	3901.80	447.10	3.12	.35
Temporal pole	R	Comparison	2383.74	283.67	1.70	.22
		DLD	2320.25	337.10	1.80	.29
	L	Comparison	2606.58	307.33	1.87	.26
		DLD	2522.34	374.40	2.01	.22

Relative volumes were obtained by dividing absolute volumes by intracranial volumes (ICV) and then multiplying by 100. *DLD* Developmental language disorder, *L* Left, *R* Right, *SD* Standard deviation

and ventral pathways between individuals with and without DLD. The focus of this study was on the structure of the two pathways; however, we did obtain the ICV measure in order to obtain proportional volume difference. This analysis revealed that the groups differed with respect to ICV such that the DLD group on average had relatively smaller ICV than the

Fig. 3 **a** Relative gray matter volumes of the regions of interest in the dorsal pathway. C: the comparison group; DLD: the Developmental Language Disorder group. **b** Relative gray matter volumes of the regions of interest in the ventral pathway. C: the comparison group; DLD: the Developmental Language Disorder group.

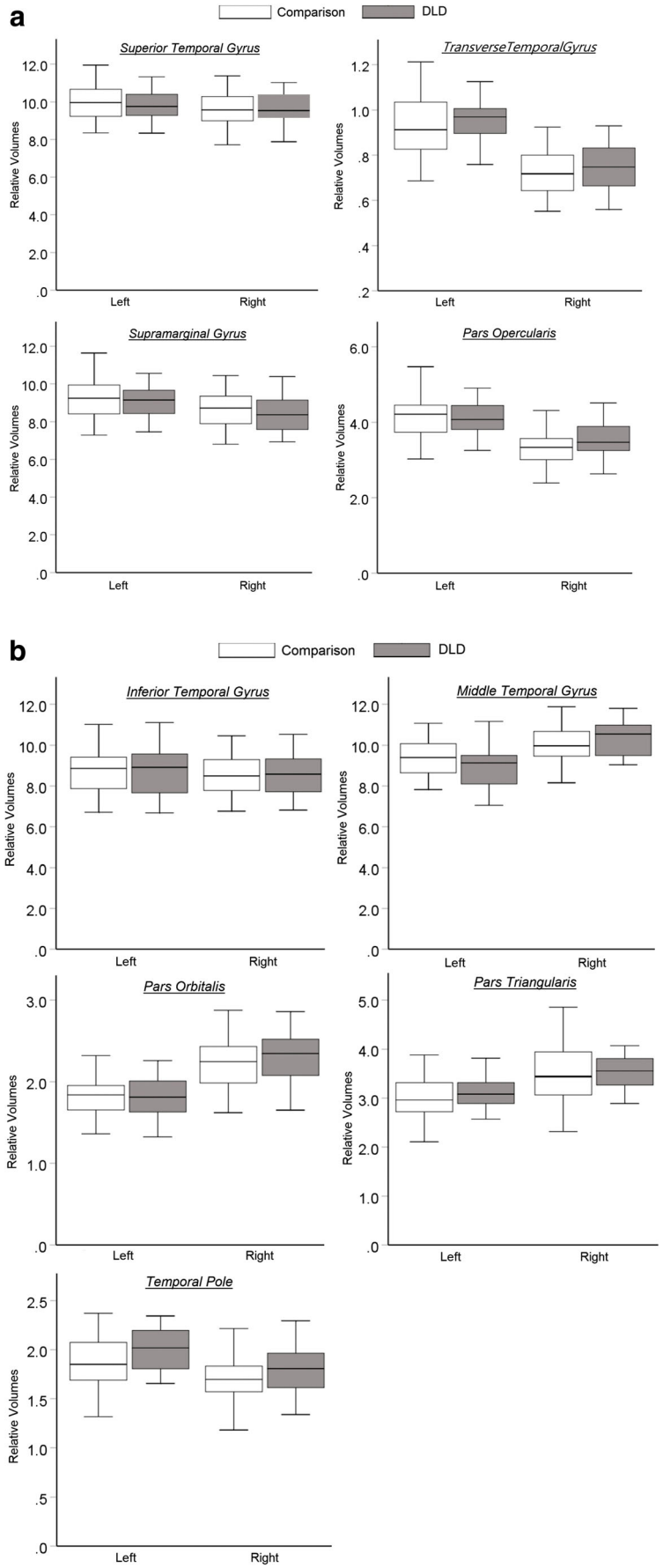
a
Comparison
DLD
Superior Temporal Gyrus
TransverseTemporalGyrus
Supramarginal Gyrus
Pars Opercularis
Relative Volumes
Left
Right
b
Comparison
DLD
Inferior Temporal Gyrus
Middle Temporal Gyrus
Pars Orbitalis
Pars Triangularis
Temporal Pole
Relative Volumes
Left
Right

Table 3 Age-by-Group interaction effects on the relative gray matter volumes of the ROIs

			F	*p*	η_p^2
Dorsal pathway					
Superior temporal gyrus (STG)	R	Age	2.22	.14	.02
		Group	.96	.33	.01
		Age x Group	.01	.94	< .01
	L	Age	.01	.93	< .01
		Group	.01	.93	< .01
		Age x Group	.02	.90	< .01
Transverse temporal gyrus (TTG)	R	Age	.07	.79	< .01
		Group	1.63	.21	.02
		Age x Group	.37	.54	< .01
	L	Age	.56	.46	.01
		Group	6.48	.01*	.07
		Age x Group	3.67	.06	.04
Supramarginal gyrus (SMG)	R	Age	2.11	.15	.02
		Group	< .01	.98	< .01
		Age x Group	.01	.92	< .01
	L	Age	.03	.86	< .01
		Group	< .01	.97	< .01
		Age x Group	.01	.92	< .01
Pars Opercularis	R	Age	1.06	.31	.01
		Group	1.72	.19	.02
		Age x Group	.40	.53	< .01
	L	Age	.06	.82	< .01
		Group	.81	.37	.01
		Age x Group	3.52	.06	.04
Ventral pathway					
Inferior temporal gyrus (ITG)	R	Age	.60	.44	.01
		Group	4.88	.03	.05
		Age x Group	.01	.95	< .01
	L	Age	1.97	.16	.02
		Group	3.02	.09	.03
		Age x Group	.96	.33	.01
Middle temporal gyrus (MTG)	R	Age	2.06	.16	.02
		Group	4.39	.04	.05
		Age x Group	.20	.66	< .01
	L	Age	6.23	.01*	.06
		Group	.11	.75	< .01
		Age x Group	.03	.87	< .01
Pars Orbitalis	R	Age	.30	.59	< .01
		Group	7.16	.01*	.07
		Age x Group	4.63	.03	.05
	L	Age	1.46	.23	.02
		Group	.57	.45	.01
		Age x Group	.60	.44	.01
Pars Triangularis	R	Age	4.01	.05	.04
		Group	.69	.41	.01
		Age x Group	5.87	.02	.06
	L	Age	6.64	.01*	.07
		Group	.59	.44	.01
		Age x Group	1.37	.24	.02
Temporal pole	R	Age	.29	.59	< .01
		Group	9.17	< .01*	.09
		Age x Group	.31	.58	< .01
	L	Age	.04	.84	< .01
		Group	11.11	< .01*	.11
		Age x Group	1.13	.29	.01

Multivariate analyses were carried out, with sex, handedness, cohort, and nonverbal IQ as covariates. An asterisk (*) indicates that the *p* value remains significant after false discovery rate (FDR) adjustment. η_p^2 : partial eta-squared; *L* Left, *R* Right

comparison group. We have reported this in an earlier paper (Lee et al. 2013). Thus, the current findings provide a replication of this in a younger group. We noted in the earlier paper that these ICV differences could be interpreted as reflecting poorer brain maturation during childhood and that differences in ICV have been reported to be associated with several developmental disorders.

Table 4 Summary of fractional anisotropy (FA) values in the fiber tracts of interest as well as in the control tracts

Fiber tracts		Group	Mean	SD
Dorsal pathway				
Superior Longitudinal Fasciculus (SLF)	R	Comparison	.31	.03
		DLD	.29	.02
	L	Comparison	.30	.02
		DLD	.29	.02
Ventral pathway				
Inferior longitudinal fasciculus (ILF)	R	Comparison	.36	.02
		DLD	.35	.03
	L	Comparison	.34	.02
		DLD	.33	.02
Inferior fronto-occipital fasciculus (IFOF)	R	Comparison	.37	.02
		DLD	.35	.02
	L	Comparison	.37	.03
		DLD	.36	.02
Uncinate fasciculus (UF)	R	Comparison	.31	.03
		DLD	.29	.03
	L	Comparison	.31	.04
		DLD	.28	.03
Control tracts				
Genu of the corpus callosum		Comparison	.47	.04
		DLD	.46	.05
Body of the corpus callosum		Comparison	.50	.05
		DLD	.47	.05
Splenium of the corpus callosum		Comparison	.50	.04
		DLD	.49	.05

DLD Developmental language disorder, *L* Left, *R* Right, *SD* Standard deviation

Dorsal pathway in DLD

No significant Age-by-Group interaction effects were found in the brain structures in the dorsal pathway. In terms of the Group main effect, the DLD group showed significantly larger gray matter volumes of the left TTG than the comparison group. TTG is a cortical marker for the primary auditory cortex, and is the first cortical stop for auditory information travelling from the brainstem nuclei and medial geniculate nucleus of the thalamus (Morosan et al. 2001). Previous studies have shown that rapid auditory processing skills are important for developing speech perception ability, which supports later language development (e.g., Bailey and Snowling 2002; Benasich et al. 2002; Cristia et al. 2014). In the DLD literature, the relationship between auditory processing and DLD has been under debate for decades. One prominent theory attributes DLD to low-level auditory perceptual difficulties (see Tallal et al. 1997, for a review), and researchers supporting this theory have found that training rapid auditory processing improved language skills in children with DLD (Merzenich et al. 1996). It is also suggested that auditory processing deficits shown in DLD arise from insensitivity to durational and amplitude envelope cues (Corriveau et al. 2007), immaturity of auditory processing (Bishop and McArthur 2005; Kwok et al. 2018), or from differences in task demands (e.g., Coady et al. 2005), instead of poor processing of auditory stimuli. In contrast, other researchers did not find evidence for a necessary role of auditory processing in DLD (Bishop et al. 1999; Helzer et al. 1996; Norrelgen et al. 2002). Bishop and McArthur (2005) argued that DLD is a heterogeneous group, and thus atypical auditory processing in DLD may occur at the individual differences level.

Our current findings showed a proportionally increased gray matter volume of the left TTG. To our knowledge, this is the first study directly examining the structure of the primary auditory cortex in individuals with DLD. At this point, it is unclear whether this volumetric enlargement is pathological (e.g., atypical synaptic pruning or atypical myelination in surrounding areas during development) or compensatory (e.g. enlargement to compensate for relatively poor auditory processing functionality in early years). Functional MRI or electroencephalography (EEG) recordings would be helpful to examine whether this structural difference associates with poor functional auditory processing outcomes in individuals with DLD.

Table 5 Fractional anisotropy (FA) in the association fiber tracts in the dorsal and ventral pathways as well as in the control fiber tracts

			F	*p*	η_p^2
Dorsal pathway					
Superior longitudinal fasciculus (SLF)	R	Age	.80	.37	.01
		Group	5.96	.02*	.07
		Age x Group	10.71	< .01*	.11
	L	Age	.37	.55	< .01
		Group	6.78	.01*	.07
		Age x Group	3.28	.07	.04
Ventral pathway					
Inferior longitudinal fasciculus (ILF)	R	Age	3.89	.05	.04
		Group	5.81	.02*	.06
		Age x Group	1.67	.20	.02
	L	Age	2.54	.11	.03
		Group	2.10	.15	.02
		Age x Group	5.41	.02*	.06
Inferior fronto-occipital fasciculus (IFOF)	R	Age	1.65	.20	.02
		Group	9.71	< .01*	.10
		Age x Group	2.23	.14	.03
	L	Age	.69	.41	.01
		Group	5.70	.02*	.06
		Age x Group	4.57	.04	.05
Uncinate fasciculus (UF)	R	Age	1.28	.26	.02
		Group	2.73	.10	.03
		Age x Group	8.52	< .01*	.09
	L	Age	.42	.52	.01
		Group	9.05	< .01*	.10
		Age x Group	4.31	.04	.05
Control tracts					
Genu of the corpus callosum		Age	.34	.56	< .01
		Group	.03	.86	< .01
		Age x Group	1.06	.31	.01
Body of the corpus callosum		Age	.29	.59	< .01
		Group	2.71	.10	.03
		Age x Group	1.06	.31	.01
Splenium of the corpus callosum		Age	< .01	1.00	< .01
		Group	.08	.77	< .01
		Age x Group	.22	.64	< .01

Multivariate analyses were carried out, with sex, handedness, cohort, and nonverbal IQ as covariates. An asterisk indicates that the *p* value remains significant after false discovery rate (FDR) adjustment. η_p^2 : partial eta-squared; *L* Left, *R* Right

In addition, we also showed differences in white matter microstructure in bilateral SLF between the DLD and the comparison group, which is consistent with previous findings (Verly et al. 2018; Vydrova et al. 2015; but see Morgan et al. 2018). Moreover, we add new information by showing atypical FA changes across the study age in the right SLF in the DLD group (see Fig. 4). The DLD group had a non-significant change in FA across age, whereas the comparison group had a significantly increased FA across age. The SLF in both hemispheres contribute to language processing. Previous studies showed that the right SLF was positively correlated with executive function skills, set shifting in particular, while the left SLF was more correlated with language, specifically the processing of complex syntactic structures (Dick et al. 2014; Friederici and Gierhan 2013; Urger et al. 2015). Broce et al. (2015) further showed that microstructural properties of both left and right AF/SLF predict receptive and expressive language outcomes in children, suggesting the potential importance of the contribution of the non-language dominant right SLF to language development and learning. The current

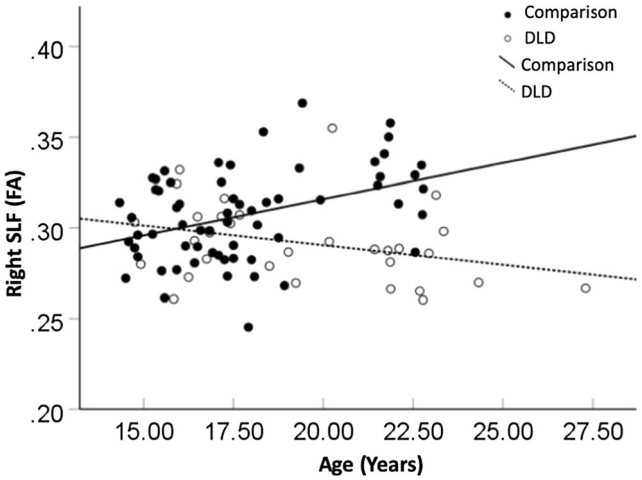

Fig. 4 Significant age-by-group interaction effect on fractional anisotropy (FA) measure in the right superior longitudinal fasciculus (SLF) in the dorsal pathway.

findings seem consistent with recent studies showing poor executive functioning in individuals with DLD (Henry et al. 2012; Vissers et al. 2015).

Ventral pathway in DLD

No significant Age-by-Group interaction effects were found in the brain structures in the ventral pathway after correcting for multiple comparisons. In addition, the DLD group showed significantly larger relative volumes of the right *pars orbitalis* in the IFG, as well as bilateral temporal poles. Both regions are involved in lexical-semantic processing (Saur et al. 2008; Lambon Ralph et al. 2009); however, at this point, it is unclear what may account for this volumetric increase. Right IFG is connected with the basal ganglia to modulate response inhibition performance (Aron et al. 2004; Wiecki and Frank 2013). Given that individuals with DLD had abnormal volumes of the basal ganglia (Lee et al. 2013), one possibility is that abnormality in the basal ganglia disrupts the normal development reduction in synapse number, resulting in atypical pruning and compromising IFG function.

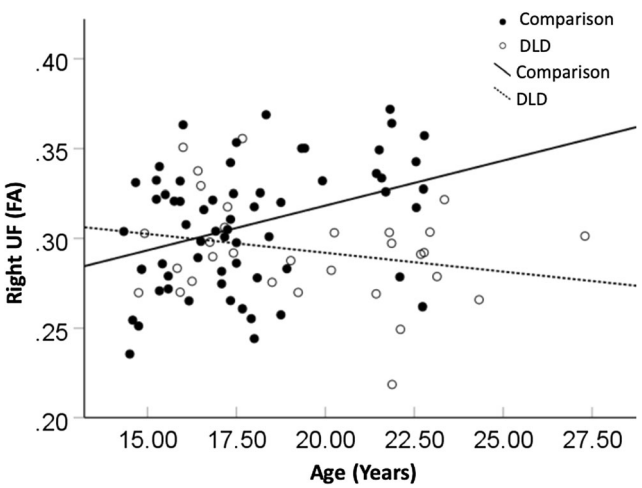

Fig. 5 Significant age-by-group interaction effect on fractional anisotropy (FA) measure in the right uncinate fasciculus (UF) in the ventral pathway.

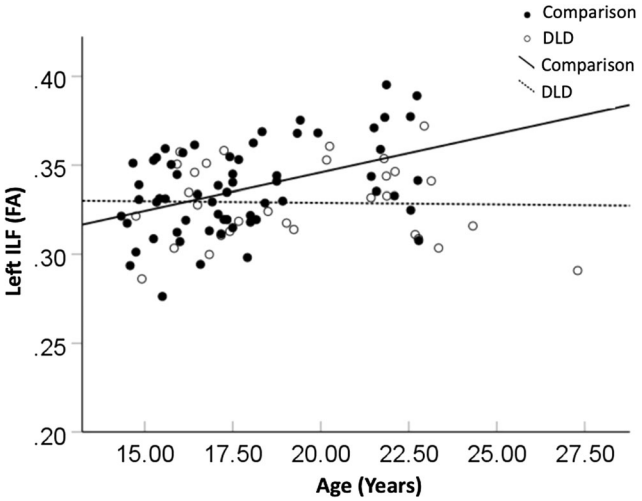

Fig. 6 Significant age-by-group interaction effect on fractional anisotropy (FA) measure in the left inferior longitudinal fasciculus (ILF) in the ventral pathway.

With regard to the FA measure, we showed an Age-by-Group interaction effect on the right UF (see Fig. 5) and the left ILF (see Fig. 6). That is, individuals with DLD did not show comparable FA increase across age in the right UF and the left ILF when compared with those without DLD. In addition, the DLD group had lower FAs than the comparison group in most of the fiber tracts in the ventral pathway, including the bilateral IFOF, the left UF, and the right ILF.

Taken together, these results indicate that the microstructural development of the ventral pathway is affected in individuals with DLD. Given that the general function of the ventral pathway is to support lexical-semantic aspects of language (Hickok and Poeppel 2004; Friederici and Gierhan 2013; Saur et al. 2008), the current findings suggest a potential biological correlate of lexical-semantic deficits in adolescents/young adults with DLD. In contrast to morphosyntax, relatively less attention has been paid to lexical-semantic development in DLD. In the past decade, growing evidence shows that individuals with DLD not only have morphosyntactic deficits, but they also have lexical-semantic weakness (Nation 2014). Our findings highlight the need for more work on lexical-semantic development across a wide range of age in DLD.

It is important to bear in mind that these white matter tracts of interest are not exclusive to language function. For example, the UF plays a critical role in the formation and retrieval of episodic memory (McDonald et al. 2008), while the ILF involves object recognition and visual memory in addition to lexical-semantic processing (Ortibus et al. 2012; Shinoura et al. 2007). Thus, the next step is to explore the brain-behavior relationships by examining the effect of structural

differences on functional outcomes in DLD. The potential results would contribute to our understanding of the role of domain-general cognitive factors in language development and learning.

DLD: an emergent outcome from interactions between biology and environment

In the current study, we showed structural differences in the dorsal and ventral language pathways in individuals with DLD. DLD is a neurodevelopmental disorder, wherein language impairment gradually unfolds over time in the maturation of the brain as it is gradually shaped by genetic as well as environmental factors (Bishop 2000; Karmiloff-Smith 1998; Mareschal et al. 2007; Westermann 2016). Our findings raise the question of the causal relationship between brain structures and language function in DLD. On the one hand, it is possible that structural differences reflect a biological prerequisite for DLD, and thus poor language acquisition and learning may be considered as being dependent on existing structural alterations in the brain. On the other hand, it is also possible that structural differences are simply reflective of an emergent outcome arising from abnormal language development. It is unlikely that we can tease apart the contributions of biological and environmental factors to language development in our adolescent/adult subjects. However, it is not any easier to tease them apart in younger children or infants, because the influence of environmental factors on language development begins before birth (Hepper 2015; Moon et al. 2013; Partanen et al. 2013). It is likely that a dynamic interaction between neurobiological predispositions and language function continues during development and maturation (Karmiloff-Smith 1998; Tomblin and Christiansen 2010).

Due to the complexity of the mechanisms underlying DLD, it is important to use converging methods in the same study to examine DLD at a multi-systems level (e.g., genetic, neural, cognitive, behavioral, environmental) (Tomblin and Christiansen 2010). Better understanding of the multi-level mechanisms will help us develop different types of interventions addressing the phenotypic heterogeneity in DLD. For example, behavioral genetic studies of DLD could inform us how allelic variations influence a person's response to language interventions, or brain imaging studies could inform us the behavioral or cognitive strengths/weaknesses of individuals with DLD as well as their compensatory strategies in coping with language difficulty.

Conclusion

In the current study, we showed structural differences in the dorsal and ventral language pathways between individuals with and without DLD, and these differences varied between the ages of 14 and 27. These are preliminary data only, and future studies are needed to examine the role of age in the brains of DLD. Language development is supported by distributed neural networks connecting both cortical and subcortical regions throughout the brain (Lieberman 2002; Mesulam 1990). While the current study focused on the cortical language-relevant gray matter volumes and white matter fiber tracts in DLD, it would be also important to address how subcortical networks interact with the cortical language pathways to support language development and learning. In addition, it is important to examine what and how environmental factors play a role in atypical language development, given that subtle environmental changes are also possible to compound over time (e.g., low socioeconomic status leading to less variation or poor quality of language input).

Despite significant findings, the study has several limitations. First, in order to obtain a wide age range we recruited two cohorts using different recruitment approaches. Ideally, we would have used a longitudinal design or at least the same recruitment methods. The former would have required considerable time and would likely face considerable attrition since the age range spanned the transition from adolescence to adulthood with attendant changes residence. In the latter case, it is difficult to devise a common recruitment method for adolescents and young adults given different living and life activities. To address the possible cohort effects, we used statistical methods to ensure that groups were comparable between the two cohorts with regard to language status. Moreover, to be conservative, we put Cohort as a covariate in all analyses. In future studies, it would be more ideal to recruit a larger sample using the same recruitment methods. Second, we used FreeSurfer to obtain automatic gray matter segmentation, as well as using JHU white matter tractography atlas to label the main fiber tracts of interest. Thus, we were not able to easily delineate different portions of the STG, or to measure FA in distinct components of the SLF (Friederici 2009; Kamali et al. 2014; Martino et al. 2013). Tractography will be helpful in identifying the subcomponents of the fiber tracts. Third, this is a cross-sectional study design, with very large age ranges and relatively few participants in each age banding. And there were more female subjects participating in the current study. Thus, caution needs to be taken when interpreting the results pertaining to the differential course of brain development as a function of language status. Longitudinal designs using growth curve analysis will be more appropriate to directly address this issue.

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Compliance with ethical standards

This work was supported by the National Institute on Deafness and Other Communication Disorders (NIDCD) awarded to Dr. Tomblin [Grant R21DC013733]. All authors declare that they have no conflict of interest. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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