Received: 26 January 2017 | Accepted: 30 October 2017
DOI: 10.1111/desc.12647

PAPER

WILEY Developmental Science

Vocabulary growth rate from preschool to school-age years is reflected in the connectivity of the arcuate fasciculus in 14-year-old children

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Funding information
The National Key Basic Research Program of China (2014CB846103), the Key Project of Philosophical and Social Science Foundation, Ministry of Education (11JZD041), the National Natural Science Foundation of China (31271082, 31500886, 31671126), the Fundamental Research Funds for the Central Universities (2017XTCX04), Grant #CUHK8/CRF/13G, the Interdiscipline Research Funds of Beijing Normal University, the Agence Nationale de la Recherche (ANR-11-BSV4-014-01, ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02 PSL*), the China Scholarship Council, the China Postdoctoral Science Foundation Funded Project (2016M591098), and the NSFC-CNRS Joint Research Project Grant (31611130107)

Abstract

The acquisition of language involves the functional specialization of several cortical regions. Connectivity between these brain regions may also change with the development of language. Various studies have demonstrated that the arcuate fasciculus was essential for language function. Vocabulary learning is one of the most important skills in language acquisition. In the present longitudinal study, we explored the influence of vocabulary development on the anatomical properties of the arcuate fasciculus. Seventy-nine Chinese children participated in this study. Between age 4 and age 10, they were administered the same vocabulary task repeatedly. Following a previous study, children's vocabulary developmental trajectories were clustered into three subgroups (consistently good, catch-up, consistently poor). At age 14, diffusion tensor imaging data were collected. Using ROI-based tractography, the anterior, posterior and direct segments of the bilateral arcuate fasciculus were delineated in each child's native space. Group comparisons showed a significantly reduced fractional anisotropy in the left arcuate fasciculus of children in the consistently poor group, in particular in the posterior and direct segments of the arcuate fasciculus. No group differences were observed in the right hemisphere, nor in the left anterior segment. Further regression analyses showed that the rate of vocabulary development, rather than the initial vocabulary size, was a specific predictor of the left arcuate fasciculus connectivity.

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RESEARCH HIGHLIGHTS

- Vocabulary development from age 4 to age 10 is reflected in the left arcuate fasciculus at age 14.
- The poor group showed lower FA of the AF-direct and AF-posterior compared with the catch-up and good groups.
- Vocabulary growth rate significantly predicts the FA of both AF-direct and AF-posterior.

1 | INTRODUCTION

Vocabulary development, as a critical aspect of natural language acquisition, is one of the most essential aspects of child development. It has been found to be an important precursor of children's academic achievement and behavioral function (Morgan, Farkas, Hillemeier, Hammer, & Maczuga, 2015). Using longitudinal methodology, numerous studies have described the developmental trajectories of early vocabulary development for toddlers (e.g., from birth to 46 months, Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Rowe, Raudenbush, & Goldin-Meadow, 2012; Vagh, Pan, & Mancilla-Martinez, 2009). However, lexical development does not cease in the toddler period; it continues to progress rapidly after they enter school and also overlaps with reading acquisition during formal schooling (Nation & Coady, 1988; Verhoeven, van Leeuwe, & Vermeer, 2011). Thus, understanding vocabulary development in school-age children is of great value for both psychologists and school educators. A recent study focused on long-term vocabulary development from preschool to school-age years, and found a diversity of developmental trajectories (e.g., from age 4 to age 10; Song et al., 2015). As previous studies have suggested, such long-term language learning experience may be reflected in the maturation of certain neural circuits (Wandell, 2011; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012). However, at present, little is known about the neural correlates of long-term vocabulary development.

There is a broad consensus that children vary widely in the initial size and in the growth rate of their vocabulary (Fernald & Marchman, 2012; Rowe et al., 2012; Song et al., 2015). Two recent studies have shown that, compared with initial size, the pace of vocabulary growth was a more important predictor of subsequent language and reading development (Rowe et al., 2012; Song et al., 2015). Rowe et al.'s (2012) study found that the pace of vocabulary growth predicted later language proficiency. Song et al. (2015) also reported that the growth rate of vocabulary development explained more variance of later reading than initial vocabulary size. These studies highlight the importance of growth rate on ultimate achievement. However, the neurobiological basis of this developmental indicator, and particularly the link between vocabulary growth rate and brain maturation, is largely unknown. Until now, there has been only one study that has explored the influence of early vocabulary growth on later cortical structure (Asaridou, Ouml, Demir-Lira, Goldin-Meadow, & Small, 2017). In that study, researchers characterized vocabulary developmental trajectories for 18 children from 14 months to 58 months. They found that, rather than the initial vocabulary level, the pace of vocabulary growth predicted cortical thickness of the left supramarginal gyrus at 10 years old (Asaridou et al., 2017). This study highlights the influential effects of early vocabulary development on brain structure. However, vocabulary development does not stop at 58 months, and it would therefore be interesting to take into account a more complete picture of vocabulary development until adolescence. Furthermore, language acquisition is a complex cognitive process that requires communication between a large network of brain regions centered around the sylvian fissure (Catani & Jones, 2005; Dehaene-Lambertz, Hertz-Pannier, & Dubois, 2006). The long fiber pathways connecting these regions play an important role in supporting language and reading development (Ben-Shachar, Dougherty, & Wandell, 2007; Wandell & Yeatman, 2013; Yeatman et al., 2011). There is evidence that the long fiber pathways connecting temporal and frontal cortex (the arcuate fasciculus) are not mature at birth and continue to develop even beyond the school-age years (Brauer, Anwander, & Friederici, 2011; Perani et al., 2011). This may suggest that later language experience and other related factors play an important role in shaping the development of white matter connectivity. However, no association between white matter connectivity and language development was observed in Asaridou et al.'s study. This may be due to sub-optimal analysis of the diffusion images, using tract-based spatial statistics (Smith et al., 2006), in which images of all subjects were aligned into a common template and analyzed voxel-wise. Compared with tractography analyses in each child's native space, this method may not fully capture the inter-individual variability among children (Vandermosten, Boets, Wouters, & Ghesquière, 2012). Another possible reason is the small sample size (n = 18) in their study. Therefore, it seems desirable to further study the relationship between vocabulary development and the maturation of white matter tracts, using state-of-the-art tractography methods, a large sample size, and covering a longer stretch of vocabulary development.

During the past two centuries, neuroscientists have consistently suggested that the arcuate fasciculus (AF) connecting the temporal and frontal cortex is the most important language-related pathway in human beings, from the pioneering postmortem/lesion studies of nineteenth-century neuroanatomists (Broca, 1861; Burdach, 1819; Dejerine, 1895; Reil, 1812; Wernicke, 1874) to the fine reconstruction of this fiber tract with diffusion tensor imaging (DTI) tractography technique (Catani & Jones, 2005; Catani & Thiebaut de Schotten, 2008; Glasser & Rilling, 2008). Recently, Catani and Jones (2005) demonstrated that the AF consists of three subcomponents: the first is a direct pathway connecting the inferior frontal gyrus with the superior temporal regions (the long segment of the AF, AF-direct); the second is a pathway connecting the inferior frontal gyrus with the inferior parietal cortex (the anterior segment of the AF, AF-anterior); the third is a pathway connecting the inferior parietal cortex with the superior temporal regions (the posterior segment of the AF, AF-posterior). The respective functions of the three segments have been studied using intraoperative electrostimulation, which suggested that the AF-direct is involved in phonological processing, the AF-anterior in articulation and the AF-posterior in speech perception (Duffau, 2008). This AF model has become largely accepted in language and reading research (Catani et al., 2007; López-Barroso et al., 2013; Thiebaut de Schotten, Cohen, Amemiya, Braga, & Dehaene, 2014; Vandermosten, Boets, Poelmans et al., 2012; Zhao, Thiebaut de Schotten, Altarelli, Dubois, & Ramus, 2016). Across these studies, the asymmetry of the AF has been found to be a prominent feature of human brain development and to be associated with language-related skills (Catani et al., 2007). In a recent study, combining DTI tractography and functional MRI in 21 healthy adults, López-Barroso et al. (2013) found that word learning ability was correlated with the microstructural property of the left AF-direct, and it was also related to the functional connectivity between left inferior frontal and superior temporal regions. This study provides reliable evidence for the role of the AF-direct in auditory–motor integration during word learning (López-Barroso et al., 2013), although such a short-term learning experiment in adults is not equivalent to the long-term natural learning of language in childhood. Thus, elucidating the role of the AF and its laterality in natural vocabulary development seems in order.

The present study aims to explore white matter connectivity among different developmental trajectories of vocabulary growth in a group of 79 participants followed from age 4 to 14. From age 4 to age 10, children's language ability was measured by a standard vocabulary knowledge test, and their developmental trajectory was classified into one of the three groups proposed by Song et al. (2015). At age 14, the children underwent MRI, including diffusion imaging. Using DTI tractography in each child's native space, the direct, anterior and posterior segments of the AF were carefully delineated in both hemispheres. This allowed us to test to what extent the connectivity and lateralization of the three segments of the AF differ between the three trajectory groups, and is predicted by initial size and growth rate of individual trajectories. Based on the studies of López-Barroso et al. (2013), Asaridou et al. (2017) and Catani et al. (2007), we may more specifically expect a group difference on the direct segment of the AF (and its lateralization index), and an association between vocabulary growth rate and AF connectivity.

2 | METHOD

2.1 | Participants

Seventy-nine Chinese children participated in this study. All participants came from a large ongoing longitudinal study of Chinese language and literacy development that has taken place since 2000 (Lei et al., 2011; Song et al., 2015). In the original longitudinal study, 338 children were selected from a standardization study that was designed to develop the Chinese version of the Communicative Development Inventory (CCDI; Tardif, Fletcher, Zhang, & Liang, 2008). All children in the CCDI study were recruited from the mother-child healthcare clinics of Beijing and were selected to be demographically representative of the city. They were all native Mandarin speakers with normal IQ based on the Chinese version of Gesell Developmental Schedules (Lin, Li, & Zhang, 1987). According to the healthcare records, none of the children had reported mental, physical, or sensory difficulties. Of the 338 children, one-third had top CCDI scores (above 90%), one-third had medium CCDI scores (i.e., 45–55%), and the rest had CCDI scores below 10%. The 338 children came from families with a variety of socioeconomic status levels (Zhang et al., 2013). Thus, the original longitudinal sample is a population-based sample of typically speaking children that can reasonably represent the entire city.

Figure S1 depicts a flow chart of participant recruitment from the original sample of participants to the sample of n = 79 children in this paper. As shown in Figure S1, at age 1, the original sample of participants is 338. From age 2 to age 11, children were tested annually on a variety of reading and language-related measures. The sample number slightly decreased year by year. At age 14, we mailed invitation letters for the MRI study to all the participants remaining at age 11 (n = 291). In the next step, we directly made telephone calls to the parents who signed the agreement from the invitation letter (n = 107). Of these children, 28 had counter-indications to MRI scan for various reasons (e.g., metal braces). Finally, we had 79 volunteers in the DTI study. We compared demographic and behavioral variables of the children that were included this study vs. those excluded. Independent-samples t tests showed that there was no significant difference between the two groups in age, gender, IQ, mother's education level and word reading ability (tested at age 11) (all ps < .05). All 79 participants had normal IQ (above the 10th percentile on the Raven's Standard Progressive Matrices, Raven & Court, 1998). Mother's education information was also collected with a standard 7-point scale, which has been widely used as a proxy for family socioeconomic status in previous studies (Lei et al., 2011; Song et al., 2015). Informed written consent was obtained from both the parents and their children. Ethical approval for the present study was obtained from the Institutional Review Board of Beijing Normal University Imaging Center for Brain Research.

As part of a large ongoing longitudinal project, children were tested on a variety of reading-related behavioral measures annually. Considering the aim of the present study, we focused on the language-related task. Between age 4 and age 10, they were administered vocabulary tasks. When children were aged 14, diffusion MRI data was collected on 79 children. Three participants had more than three missing data points on the vocabulary test, so they were excluded from the association analysis between language development and brain structure.

2.2 | Behavioral measures and analysis

2.2.1 | Vocabulary definition task

This vocabulary definition task was translated and adapted for Chinese children from the vocabulary subtest of the Stanford-Binet Intelligence Scale (Thorndike, Hagen, & Sattler, 1986). The high reliability and validity of this subtest have been documented in Thorndike et al. (1986). The testing process was in line with previous studies in alphabetic languages (e.g., Gathercole, Service, Hitch, Adams, & Martin, 1999; Lervåg & Aukrust, 2010). For instance, the experimenters asked children, "What is a postman?" The child's task was to provide the definition of the word. Then the experimenters scored the answer according to the number of important semantic features provided by children. For each item, 1 point was given for each feature and the maximum score was 2. Usually, a complete definition should include the proper semantic category and one or more features. For example, for the target word postman, a 2-point answer is "a person whose job is to collect and deliver letters". A 1-point answer is "deliver the letter". A 0-point answer is "catch the thief" or that the child just repeated the word. The model answers (with possible key features underlined in the text) of all the tested words were listed in the test manual. Two well-trained experimenters rated children's responses. They followed a formal scoring scheme from the test manual and the inter-rater reliability between the two experimenters was high ($r > 0.9$). We tested children's vocabulary ability on all children of the original longitudinal study (n = 291–309 for ages 4–10). Internal consistency test based on these children showed that the reliability of the test is reasonable and increased with age (Cronbach's α = 0.6–0.8 for ages 4–10). Little direct evidence on the criterion-related validity for the Chinese version of this test is available, but a number of previous Chinese studies have used this task and confirmed it as a reasonable proxy for Chinese vocabulary knowledge (Chow, McBride-Chang, & Burgess, 2005; Lei et al., 2011; Liu & McBride-Chang, 2010; McBride-Chang et al., 2005; Su et al., 2017; Zhang et al., 2013).

From age 4 to age 8, there were 32 items. At age 9, more tests tapping children's attention were added. Given that the testing time for a child had to be limited to two hours to avoid them becoming tired, we did not measure vocabulary knowledge at this age. At age 10, 14 new items were added to avoid a ceiling effect.

2.2.2 | Fitting vocabulary developmental trajectories

As part of a larger longitudinal study examining children's language development (n = 264, including all the participants of the present study) (Song et al., 2015), the language developmental trajectories of all the participants (n = 76) in the present study were clustered into three subgroups: the consistently good (n = 24), catch-up (n = 37) and consistently poor (n = 15) groups, respectively. That study first used linear growth models to transform vocabulary scores of participants into two parameters, the intercept (starting point) and the slope (growth rate) (Rogosa, Brandt, & Zimowski, 1982). In a second step, a clustering nearest centroid sorting method was performed to classify the participants into several subgroups. A detailed description of the statistical analysis may be found in the previous study (Song et al., 2015). Therefore, in the present study, each child belonged to a specific group and had two indices (intercept and slope) representing his/her developmental trajectory from age 4 to age 11.

Some earlier studies focusing on toddlers' language development (before 30 months) described the growth trajectories using quadratic models (Fernald & Marchman, 2012; Huttenlocher et al., 1991). Despite the different age range in the present study (age 4 to age 11), we fitted the scores by the quadratic model as well. The total variance explained (R-square) was 0.796 in the linear model and 0.857 in the quadratic model, thus the R-square change was only 0.061. We therefore chose to focus on the intercept and slope here, to remain consistent with the previous study of Song et al. (2015).

2.2.3 | Word reading task

In order to test the specific relationship between vocabulary development and white mater structure, we included parameters of reading development as control variables. The word reading task was measured repeatedly from age 5 to age 11, to almost overlap with the time range of the vocabulary development.

In this task, there are 150 Chinese characters with increasing difficulty and decreasing frequency. All of these characters match the properties of school-level Chinese regarding number of strokes, character frequency, and the proportion of phonograms (Shu, Chen, Anderson,, Wu, & Xuan, 2003). It showed excellent reliability and validity (test–retest r = 0.84–0.97 for grades 1–6; Cronbach's α = 0.97; split-half consistency = 0.89; correlation with another character reading measure = 0.921) in previous studies using the same task (Liu et al., 2017; Song et al., 2015; Xue, Shu, Li, Li, & Tian, 2013). In this task, children were visually presented with the 150 characters. Their task was to name the characters as accurately as possible. There was no time limit and the test was terminated if participants did not succeed on 15 consecutive items. For each item, 1 point was given if the child named the character correctly. This task has been widely used to evaluate Chinese children's reading ability (Lei et al., 2011; Pan et al., 2011).

2.2.4 | Fitting reading developmental trajectories

In line with vocabulary development, we fitted the developmental trajectories of reading by linear growth models. Indeed, we chose the linear function based on the following reasons. First, in our preliminary analysis, we fitted the reading scores by linear and quadratic models separately. We found that the R-square change between the two models was tiny. So we chose the simpler linear model. Furthermore, we plotted the means of the reading scores from age 5 to age 11 and also looked at a number of individual growth curves. They all looked linear, thus confirming our selection of the linear model. Thus the reading development of each individual was transformed into two parameters, the intercept (starting point) and the slope (growth rate). Then the two developmental parameters were used as covariates in further analyses.

2.3 | MRI data acquisition and analysis

We used a 3 Tesla MRI scanner (Siemens Trio, Germany) to collect the diffusion weighed imaging (DWI) data of the children. A single-shot spin-echo echo-planar imaging sequence was applied (TR = 8000 ms; TE = 89 ms; acquisition matrix = 128 × 128; field of view = 282 × 282 mm^2; slice thickness = 2.2 mm with no gap). The DWI sequence was repeated twice and the resolution was 2.2 × 2.2 × 2.2 mm^3. There were 30 diffusion-weighted directions and the diffusion weighting factor b-value was 1000 s/mm^2.

The registration of the raw DWI images and correction for subject motion and geometrical distortions were performed using the ExploreDTI software (http://www.exploredti.com; Leemans & Jones, 2009). The Levenberg–Marquardt nonlinear regression was then used to fit the tensor model (Marquardt, 1963). The fractional anisotropy (FA) was computed based on the eigenvalues of the diffusion tensor (Basser & Pierpaoli, 1996). Then the whole-brain tractography was performed using an interpolated streamline algorithm with a step length of 0.5 mm and maximum angle threshold of 35°. Voxels that showed an FA value below the threshold 0.2 from the tractography were excluded (López-Barroso et al., 2013; Thiebaut de Schotten et al., 2014). Finally, we imported the diffusion tensor maps and tractography data into the software TrackVis (http://www.trackvis.org; Wedeen et al., 2008).

A region-of-interest (ROI) approach was used to extract the tracts of interest (Figure 1a). They are the direct, anterior and posterior segments of the arcuate fasciculus, respectively. The definition of the ROIs was performed blinded to the developmental trajectory group. The protocol for defining the ROIs for each fiber tract was based on a study by Catani and Jones (2005). Following previous studies (Rojkova et al., 2016; Zhao et al., 2016), we automated some steps of the tract dissection in order to minimize the subjective variability related to manual dissection. ROIs were defined on the MNI152 template provided with the FMRIB Software Library package (FSL; http://www.fmrib.ox.ac.uk/fsl/). For each subject, the FA map was registered to the MNI152 template using Advanced Normalization Tools (ANTs, http://www.picsl.upenn.edu/ANTS/), which combine affine with diffeomorphic deformations (Avants, Epstein, Grossman, & Gee, 2008; Klein et al., 2009). The inverse deformation was then applied to the ROIs defined on the MNI152 template in order to bring them to the native space of every participant. Finally, individual dissections of the tracts were visually inspected in each participant's native brain space and corrected by two anatomists (MS and AC). Average FA, perpendicular (radial diffusivity, RD), and parallel diffusivities (axial diffusivity, AD) which are indirect measures of the white matter microstructural properties, were extracted along each tract. Furthermore, we calculated the lateralization index (LI) for each tract using the formula (R−L)/(R+L) (Zhao et al., 2016). Moreover, we chose the inferior fronto-occipital fasciculus (IFOF) as a control tract (the protocol for defining the ROIs followed Catani & Thiebaut de Schotten, 2008). Indeed this tract was found to be more related to the visual-orthographic processing in reading tasks than to spoken language tasks as used in the present study (Vandermosten et al., 2012; Zhao et al., 2016). So we expected no group difference to be found for this tract.

2.4 | Statistical analysis

Statistical analysis was performed in SPSS Statistics v.20 (IBM Corporation, Somers, New York). First, demographic and behavioral differences between the three developmental groups were tested through one-way ANOVA tests. Second, in order to test the FA and FA lateralization differences of the different segments of the arcuate fasciculus between the three groups, repeated measures ANOVAs were performed in each hemisphere, with segment of the arcuate fasciculus as within-subject variable, group as between-subject variable, and with age, sex, IQ, mother's education and whole-brain mean FA as covariates (without whole-brain mean FA in the lateralization tests). The results were further interpreted using two other diffusivity measures (AD, RD) with the same repeated measure ANOVAs. Third, in order to examine the influences of the two developmental parameters (intercept, slope) on the FA and FA lateralization of arcuate fasciculus, hierarchical linear models were used. In the first step, age, sex, IQ, mother's education and the whole-brain mean FA were entered as control variables (without whole-brain mean FA in the lateralization tests). In the second step, intercept and slope were entered as the independent variables of interest. Then the results were interpreted using the other two diffusivity measures (AD, RD) with the same regression models. Finally, to investigate the specificity of the relationship between vocabulary development and arcuate fasciculus maturation, we added parameters of reading developmental trajectories as covariates before entering the intercept and slope of vocabulary development. Results were corrected for multiple comparisons

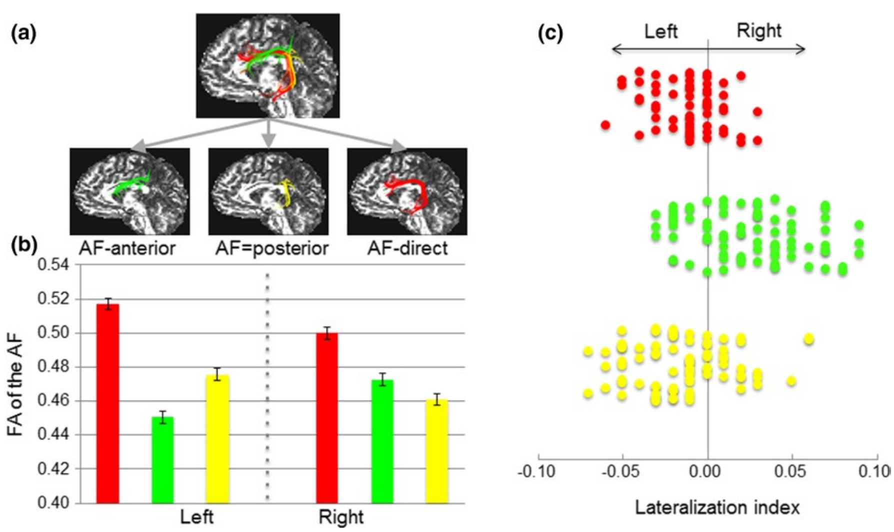

FIGURE 1 Distribution of the FA values of the arcuate fasciculus between hemispheres. (a) Illustration of the three segments of the arcuate fasciculus: red tract refers to arcuate fasciculus-direct (AF-direct), green tract to arcuate fasciculus-anterior (AF-anterior), yellow tract to arcuate fasciculus-posterior (AF-posterior). (b) FA values of the three segments of arcuate fasciculus in both hemispheres. Error bars represent standard error of the mean. (c) FA lateralization index of each individual on the three segments of arcuate fasciculus

of tracts using the False Discovery Rate (FDR) correction (Benjamini & Hochberg, 1995). In the Results section, we report uncorrected p-values and then compare them to the FDR-corrected alpha threshold q-value.

3 | RESULTS

3.1 | Group differences on demographical data and vocabulary scores

Table 1 describes the means and standard deviations of the demographical data and vocabulary scores at the six time points. Age ($F(2, 73) = 1.039$, $p = .359$) and sex ($\chi^2(2) = 0.208$, $p = .901$) did not differ between the three groups. As for IQ and mother's education level, significant group differences were found (all $ps < .05$), with higher IQ and mother's education in the good group than in the other two groups. Thus, in further analyses, IQ and mother's education level were statistically controlled.

Regarding the vocabulary test, there were significant group differences at all six time points (all $ps < .001$). Bonferroni-corrected post-hoc tests showed that the vocabulary score of the children in the good group was significantly higher than those in the catch-up and poor groups from age 4 to age 7 (all $ps < .05$), while the scores of the catch-up and poor groups did not differ significantly until age 7. From 8 years on, children in the catch-up group caught up and became significantly better than those in the poor group. The developmental trajectories of the three groups are also depicted in Figure 2d.

3.2 | General distribution of the FA values of the arcuate fasciculus

First, we checked the quality of the tract dissection. Figure 1a shows an example of fiber tracking in a representative subject. Success rates were higher than 95% on each segment of the arcuate fasciculus in both hemispheres, except for the right AF-direct, whose success rate was 87%, similar to previous studies (Catani et al., 2007; Yeatman et al., 2011). We then examined the distribution of FA values in the three segments of the arcuate fasciculus across the two hemispheres. A significant hemisphere by segment interaction was found ($F(1, 61) = 45.551$, $p < .001$) (Figure 1b). Indeed, the FA of the AF-posterior was larger than for the AF-anterior in the left hemisphere ($p < .001$), while this pattern was reversed in the right hemisphere ($p < .001$). In addition, Figure 1c shows the FA lateralization index of each tract for each subject. One sample t tests showed that the LIs of the AF-direct and AF-posterior were significantly smaller than 0 (AF-direct: $t = -5.421$, $p < .001$; AF-posterior: $t = -4.540$, $p < .001$), meaning left lateralized. While the LI of the AF-anterior was significantly larger than 0 ($t = 6.450$, $p < .001$), meaning right lateralized.

3.3 | Group differences in the diffusion parameters of the arcuate fasciculus

Repeated measures ANOVAs showed that there was a significant group by segment interaction in the FA of the left hemisphere ($F(4, 63) = 3.359$, $p = .012 <$ FDR-corrected $q = .025$), with significant group differences in the AF-direct ($F(2, 65) = 3.359$, $p = .030 <$ FDR-corrected $q = .033$) and AF-posterior ($F(2, 68) = 5.973$, $p = .004 <$ FDR-corrected $q = .033$), while no such difference was found in the AF-anterior ($F(2, 66) = 0.237$, $p = .790$). Post-hoc comparisons on the AF-direct revealed that the FA of the catch-up group was significantly higher than that in the poor group ($p = .026$) (Figure 2a). Regarding the AF-posterior, the FAs of both the catch-up and good groups were higher than those of the poor group (catch-up vs. poor, $p = .003$; good vs. poor, $p = .024$) (Figure 2a). No main effect or interaction was observed in the right hemisphere (all $ps > .05$) (Figure 2b).

Furthermore, the results were interpreted using two other diffusivity measurements (AD, RD) (Figure S2). Consistent with the FA results, a significant group by segment interaction was also found for the RD parameter ($F(4, 63) = 4.634$, $p = .002 <$ FDR-corrected $q = .025$), while no such interaction effect was found for the AD parameter ($F(2, 55) =$

TABLE 1 Scores on background information and vocabulary definition among the three groups

	1.Good group (n=24) 11 F, 13 M		2.Catch-up group (n=37) 19 F, 18 M		3.Poor group (n=15) 7 F, 8 M			
Measures	M	SD	M	SD	M	SD	F	Comparison
Age (months)	170.43	6.03	168.43	5.55	170.07	5.45	1.039	1=2=3
Raven IQ	11.38	2.63	9.89	2.31	9.53	2.45	3.584*	1>2=3
Mother's edu.	4.96	1.08	4.41	1.04	4.07	0.88	3.885*	1>2=3
Age 4 VOC	10.38	3.17	3.62	2.30	5.47	2.97	44.910***	1>2=3
Age 5 VOC	12.04	3.42	5.62	2.70	5.20	3.41	37.055***	1>2=3
Age 6 VOC	17.75	4.05	12.11	3.49	11.47	3.89	19.956***	1>2=3
Age 7 VOC	21.13	4.22	15.41	3.79	13.40	4.00	22.052***	1>2=3
Age 8 VOC	30.54	4.09	23.24	4.09	16.93	5.93	44.162***	1>2>3
Age 10 VOC	53.29	6.73	47.11	5.32	33.67	5.46	52.932***	1>2>3

Note. Age is at the time of brain scan, VOC = vocabulary definition, Edu. = education; *$p < .05$; **$p < .01$; ***$p < .001$.

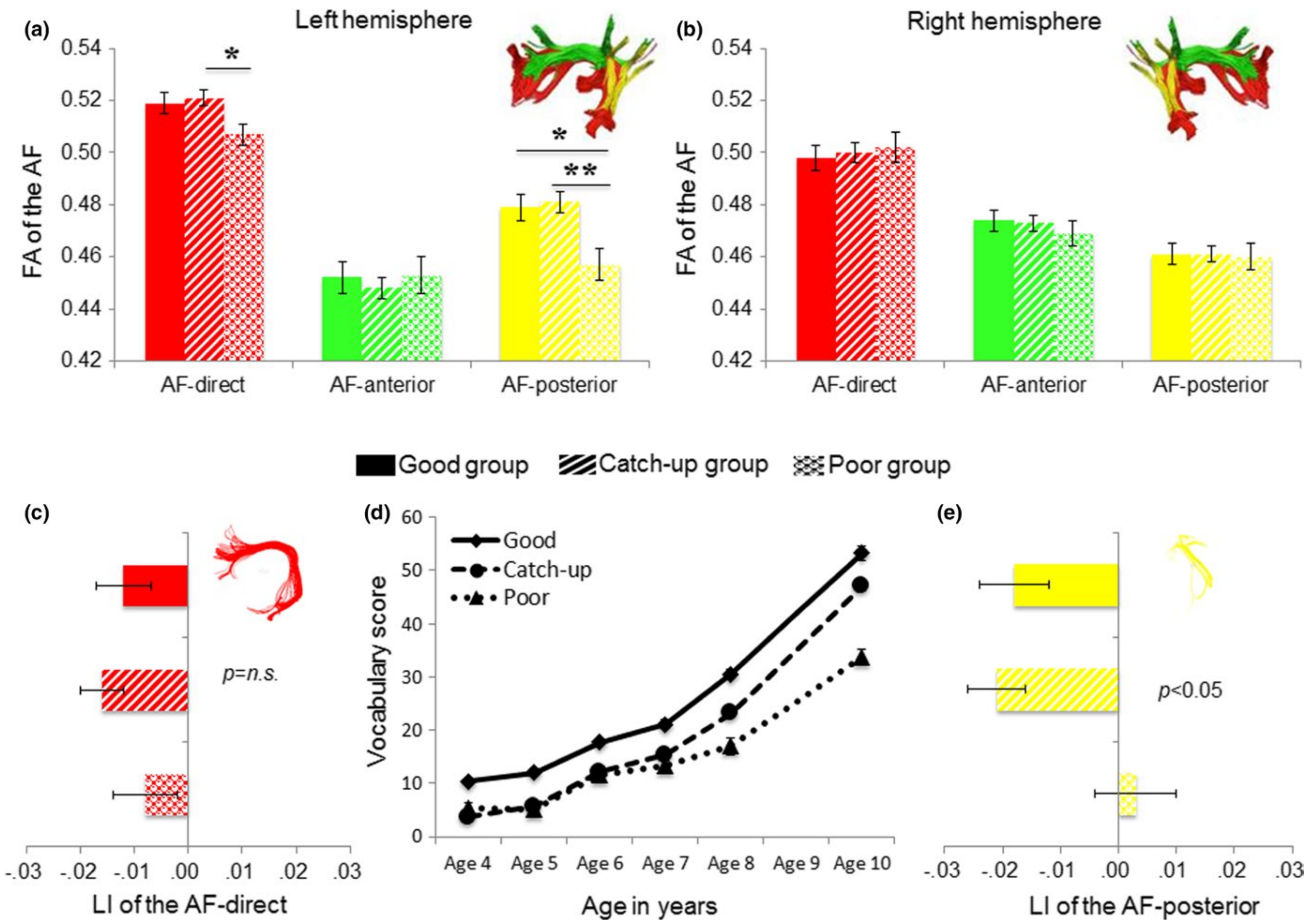

FIGURE 2 FA and FA lateralization of the arcuate fasciculus among the three developmental groups. Error bars represent standard error of the mean. (a) Group comparison of the FA values of the arcuate fasciculus in the left hemisphere. (b) Group comparison of the FA values of the arcuate fasciculus in the right hemisphere. (c) Group comparison of the FA lateralization index of the arcuate fasciculus-direct. *P*-values refer to group differences in FA lateralization index. (d) Vocabulary growth trajectories of the three groups. The Y-axis refers to the raw score of the vocabulary test. (e) Group comparison of the FA lateralization index of the arcuate fasciculus-posterior. *P*-values refer to group differences in FA lateralization index

0.114, p = .893). In particular, the interaction for RD was driven by the significant difference in the left AF-posterior between the catch-up and poor groups (p = .027), while no difference was detected for the AF-direct and AF-anterior (all ps > .05). Interestingly, the RD of the left AF-posterior in the poor group was higher than that in the catch-up group.

Finally, we analyzed group differences in the FA lateralization index of the arcuate fasciculus. As for the AF-direct, all of the three groups were left lateralized and there were no significant differences among them (p > .05) (Figure 2c). As for the AF-posterior, a marginally significant group effect was observed ($F(2, 69)$ = 4.020, p = .022 > FDR-corrected q = .017), with left lateralized distribution in the good and catch-up groups, and symmetrical distribution in the poor group (Figure 2e).

3.4 | Analysis of the control tract (IFOF)

We compared the FA and FA lateralization values of the IFOF between groups. ANCOVAs were performed in each hemisphere, with group as between-subject variable, and with age, sex, IQ, mother's education and whole-brain mean FA as covariates (as for the arcuate fasciculus). ANCOVAs showed that there were no significant group differences in the FA (left: $F(2, 68)$ = 2.732, p = .072; right: $F(2, 68)$ = 1.523, p = .225) and FA lateralization ($F(2, 69)$ = 0.807, p = .450) of the IFOF.

3.5 | Influence of vocabulary growth rate on the structure of the left arcuate fasciculus

Since group membership depends on both the initial level (intercept) and the growth rate (slope) of vocabulary development, we explored the separate influences of intercept and slope on the microstructure of the arcuate fasciculus. Regarding FA values, slope significantly predicted the FA of the left AF-direct (β = 0.246, p = .016 < FDR-corrected q = .017) and left AF-posterior (β = 0.330, p = .002 < FDR-corrected q = .017) (Table 2), after controlling the effects of age, sex, IQ, mother's education and whole-brain mean FA (Figure 3b and 3d). No correlation was found with the intercept index (all ps > .05) (Figure 3a and 3c). Notably, the two reported tracts in the regression

TABLE 2 Hierachical regression on mean FA of left arcuate fasciculus using intercept and slope of vocabulary development as predictors

		Left AF-direct		Left AF-anterior		Left AF-posterior	
Step	Variables	*Beta*	*P*	*Beta*	*p*	*Beta*	*P*
1	Age	−0.017	.870	−0.026	.813	−0.160	.131
	Sex	−0.004	.966	−0.012	.909	0.072	.448
	Raven IQ	−0.011	.915	0.144	.206	−0.060	.568
	Mother's education	−0.108	.299	0.140	.218	−0.092	.385
	Mean FA	0.622***	.000	0.511***	.000	0.562***	.000
2	Vocabulary intercept	0.123	.231	0.062	.576	−0.025	.809
	Vocabulary slope	0.246*	.016	−0.130	.222	0.330**	.002

Note. Mean FA = whole-brain mean FA; *p < .05; **p < .01; ***p < .001.

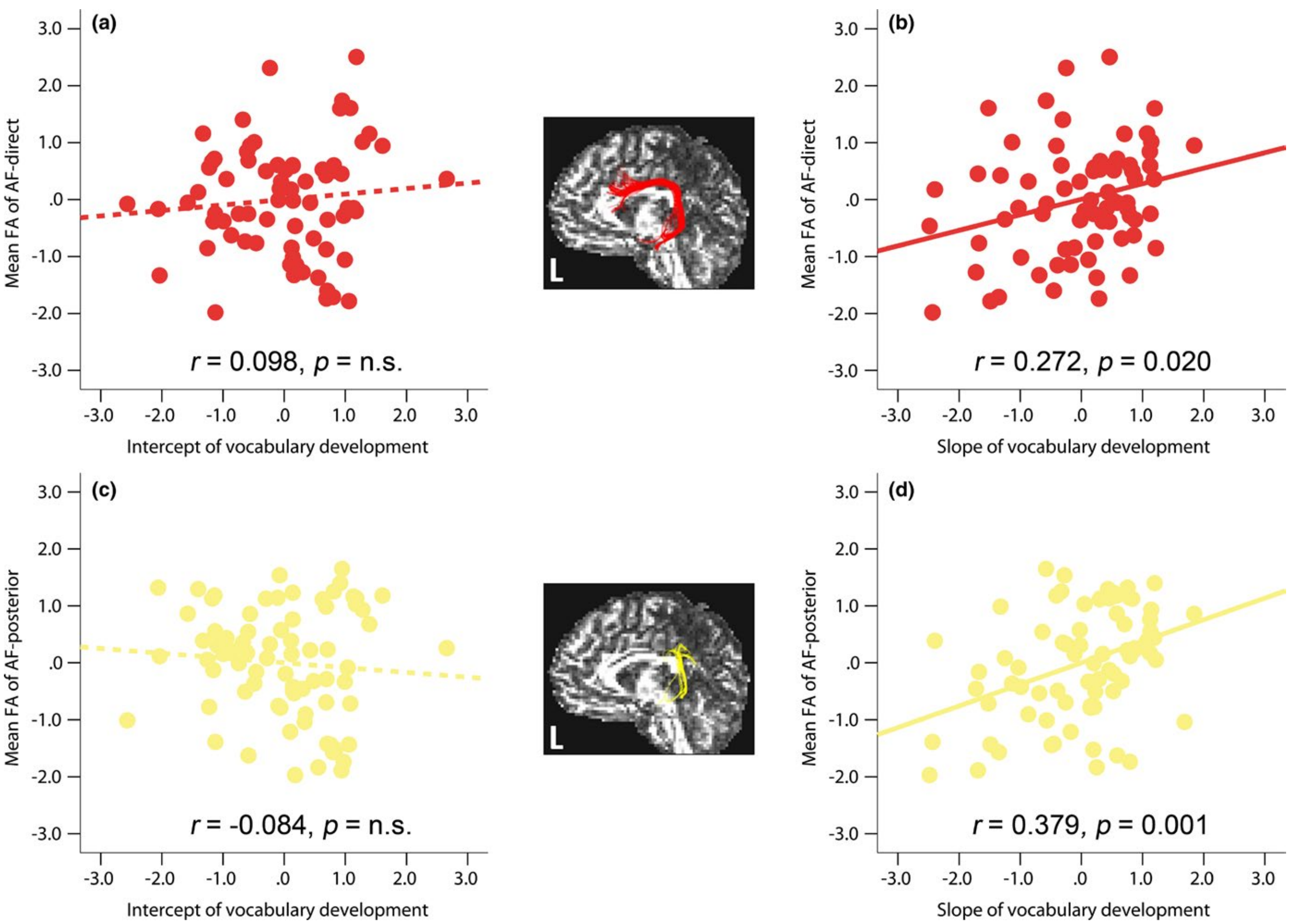

FIGURE 3 Correlation between vocabulary development and mean FA of the left arcuate fasciculus (residuals, after controlling for age, sex, IQ, mother's education and whole-brain mean FA). Red tract refers to arcuate fasciculus-direct and yellow tract to arcuate fasciculus-posterior. (a) Correlation between vocabulary intercept and mean FA of arcuate fasciculus-direct. (b) Correlation between vocabulary slope and mean FA of arcuate fasciculus-direct. (c) Correlation between vocabulary intercept and mean FA of arcuate fasciculus-posterior. (d) Correlation between vocabulary slope and mean FA of arcuate fasciculus-posterior

analyses were the same as those in the group comparisons, thus confirming the findings of the group comparisons.

Regarding the other two diffusivity measurements AD and RD, no significant correlation was observed with the AD values of the arcuate fasciculus (Table S1). With respect to the RD values, slope significantly predicted the RD of the left AF-posterior (β = −0.251, p = .004 < FDR-corrected q = .008) and there was also a trend for the left AF-direct (β = −0.150, p = .076) (Table S2). These findings, again, confirmed the findings of the FA regression analyses.

Furthermore, we examined the influence of intercept and slope on the LIs of the arcuate fasciculus. Results showed that the slope of vocabulary development significantly predicted the FA lateralization

TABLE 3 Hierachical regression on FA lateralization of arcuate fasciculus using intercept and slope of vocabulary development as predictors

Step	Variables	LI of AF-direct		LI of AF-anterior		LI of AF-posterior	
		Beta	*p*	*Beta*	*p*	*Beta*	*p*
1	Age	−0.002	.991	0.104	.421	0.299	.011
	Sex	0.094	.481	0.082	.495	−0.042	.695
	Raven IQ	−0.043	.766	−0.085	.527	0.065	.583
	Mother's education	−0.046	.751	−0.230	.086	−0.011	.929
2	Vocabulary intercept	0.046	.743	0.000	.998	0.116	.319
	Vocabulary slope	−0.085	.551	0.186	.141	−0.351**	.002

Note. $^{**}p < .01$.

of the AF-posterior (β = −0.351, $p = .002 <$ FDR-corrected $q = .017$) (Table 3). In particular, the larger the slope, the more left-lateralized the AF-posterior. The RD regression analyses revealed a similar association between vocabulary growth rate and the microstructural property of the AF-posterior (β = .315, $p = .011 <$ FDR-corrected $q = .033$; Table S2).

Finally, regression analyses on the control tract IFOF showed that neither intercept nor slope of vocabulary development predicted the FA values of the IFOF (all *ps* < .05). These results thus support the specificity of the AF (arcuate fasciculus) findings.

3.6 | Specificity of the association between vocabulary development and left arcuate fasciculus

In order to examine the specificity of the association between vocabulary development and the left arcuate fasciculus, we carried out further regression analyses by adding reading developmental parameters as covariates (Table 4). Results showed that, after controlling for reading intercept and reading slope, the vocabulary slope was still a significant predictor of the FA of the left AF-direct (β = 0.285, $p = .010$ < FDR-corrected $q = .033$) and left AF-posterior (β = 0.337, $p = .003$ < FDR-corrected $q = .033$). No prediction effect was found in the left anterior segment, nor for the intercept index (all *ps* > .05) (Table 4). These results thus confirm the findings of the previous regression analyses, showing that the relationship between vocabulary growth rate and the left arcuate fasciculus is specific to vocabulary.

4 | DISCUSSION

Combining detailed behavioral analyses and an individual-based DTI tractography methodology, the present study investigated the influence of long-term vocabulary learning experience on the structure of white matter pathways along the perisylvian system. From age 4 to age 10, children's vocabulary development was classified into three subgroups, namely consistently good, catch-up and consistently poor groups. At age 14, the three segments of the arcuate fasciculus connecting the core language brain regions (e.g., inferior frontal gyrus, inferior parietal cortex, superior temporal regions) were reconstructed in each hemisphere. Results of the group comparisons suggest that the poor group showed a decrease in the FA of both AF-direct and AF-posterior compared with the catch-up and good groups. Furthermore, after controlling for the effects of age, sex, IQ, mother's education, whole-brain mean FA and reading developmental trajectories, the vocabulary growth rate significantly predicted the FA of both AF-direct and AF-posterior. Interestingly, all the effects observed concerning FA were mirrored by similar effects with RD (radial diffusivity), but not with AD (axial diffusivity). According to previous studies, a decrease in FA accompanied by an increase in RD and a stable AD could potentially reflect a lower degree of myelination in the poor group (Song et al., 2002, 2005).

4.1 | Plasticity or predisposition

The current study revealed that the language learning experience from age 4 to age 10 is reflected in the connectivity of white matter structure in 14-year-old children. This result is open to two concurrent interpretations. First, it might reflect the modification of arcuate fasciculus microstructure as the child acquires new vocabulary over the years. Indeed, longitudinal studies describe considerable changes in the fractional anisotropy of most white matter tracts from early childhood to adolescence (Barnea-Goraly et al., 2005; Eluvathingal, Hasan, Kramer, Fletcher, & Ewing-Cobbs, 2007; Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). Such a plasticity interpretation would be consistent with a series of studies examining the influence of short-term language learning experience on the adult brain anatomy (Mårtensson et al., 2012; Stein et al., 2012). Because they collected MRI data before and after learning, such studies leave no doubt as to the direction of causation, showing that some aspects of language learning can induce brain modifications. The alternative interpretation would be that individual differences in AF connectivity reflect different predispositions for vocabulary acquisition. Indeed, it has already been suggested that differences in AF connectivity may reflect different predispositions for reading acquisition (Saygin et al., 2013), and that dyslexics show lower FA of the AF (particularly the long segment) (Vandermosten, Boets, Poelmans et al., 2012). However, most of these studies are cross-sectional, and therefore do not prove the direction of causation. A few studies have shown an influence of early MRI measures on later language skills. One study reported an influence of temporo-parietal white matter volume on reading skills (Myers et al., 2014). Another study reported that the direct segment of the arcuate fasciculus is predictive of children's reading change (between the ages

TABLE 4 Hierachical regression on mean FA of left arcuate fasciculus using intercept and slope of vocabulary development as predictors, after controlling the effect of reading development

		Left AF-direct		Left AF-anterior		Left AF-posterior	
Step	Variables	*Beta*	*p*	*Beta*	*p*	*Beta*	*p*
1	Age	−0.029	.777	−0.035	.752	−0.166	.126
	Sex	0.002	.984	−0.004	.969	0.074	.445
	Raven IQ	−0.027	.793	0.111	.324	−0.059	.583
	Mother's education	−0.083	.441	0.171	.141	−0.083	.450
	Mean FA	0.640***	.000	0.562***	.000	0.553***	.000
2	Reading intercept	−0.076	.551	0.043	.742	−0.077	.551
	Reading slope	−0.142	.290	−0.212	.132	−0.009	.950
3	Vocabulary intercept	0.129	.213	0.064	.551	−0.024	.820
	Vocabulary slope	0.285*	.010	−0.082	.458	0.337**	.003

Note. Mean FA = whole-brain mean FA; *p < .05; **p < .01; ***p < .001.

of 8 and 14) across a longitudinal interval of approximately 3 years (Gullick & Booth, 2015). Another study also reported that AF connectivity differs between children at-risk of dyslexia and control children (Wang et al., 2017). Finally, a recent study reported that the T1 intensity in the anterior segment of the left AF (presumably reflecting myelination), measured in pre-readers, predicted later dyslexia status (Kraft et al., 2016). Thus, there is evidence for both language experience and training influencing the structure of the arcuate fasciculus, and for early predispositions for language and reading abilities being reflected in the structure of the arcuate fasciculus. As we did not collect MRI data longitudinally, it is difficult for us to clearly disentangle the plasticity and the predisposition hypotheses. Another study would need to have both early and late MRI measures in order to properly answer that question.

4.2 | Compensating mechanisms of the catch-up group

The present study adds unique insights into the relationship between language ability and the structure of the AF, by extending the correlations found in the majority of previous studies (Broce, Bernal, Altman, Tremblay, & Dick, 2015; Lebel & Beaulieu, 2009; Urger et al., 2015) to the association between long-term language developmental trajectories and the structure of the AF. Previous studies reported correlations between AF microstructure/asymmetry and phonological processing or vocabulary skills at the same time point (Lebel & Beaulieu, 2009; Saygin et al., 2013; Yeatman et al., 2011). The present study revealed characteristics of the white matter pathways underlying different vocabulary developmental trajectories from age 4 to age 10. In particular, group differences were mainly reported between the poor group and catch-up/good groups, while no significant difference was detected between the catch-up and good groups. One may wonder what helped the catch-up group compensate for their low initial vocabulary scores. As there was no measured difference in the family environment (represented by mother's education) between the catch-up and poor groups, the compensation of the catch-up group may be due to more advantageous language learning experience during formal schooling. Furthermore, a previous study reported that children in the catch-up group performed similarly to the poor group on phonological and morphological skills in preschool but became significantly better at those skills than the poor group and comparable to the good group after entering primary school (Song et al., 2015). This finding suggests that the development of a wider range of language skills underlying vocabulary development may have an influence on the structure of the AF. Thus, the quality of school education and children's response to instruction may be of great importance to the development of both language and the brain. Of course, it is also possible that the difference observed here between poor and catch-up groups might reflect some aspects of the family environment that were not measured in the present study.

4.3 | The arcuate fasciculus

Regarding this specific white matter tract, we found that the AF-direct and AF-posterior were the two segments that differed between groups. Furthermore, the structure of the IFOF, connecting occipital and frontal lobes, seemed unaffected by vocabulary development. The result regarding the AF-direct is consistent with a previous study on adults, in which this segment was found to be associated with auditory–motor integration in word learning (López-Barroso et al., 2013). The present study supports this finding and extends it from short-term language learning in adulthood to long-term natural learning in childhood. As for the results regarding the AF-posterior, a previous study found that reading experience in ex-illiterates may improve the integrity of that segment (Thiebaut de Schotten et al., 2014), and the AF-posterior has also been involved in speech perception in dyslexia (Vandermosten, Boets, Poelmans et al., 2012). In addition, the AF-posterior may be involved in vocabulary development not only by its contribution to speech perception, but also by its projection to the angular gyrus (Catani & Mesulam, 2008), a region possibly involved in lexical semantic processing (Seghier, Fagan, & Price, 2010), which is important for the word definition task we used in the current study.

4.4 | Vocabulary growth rate and maturation of the AF

An interesting finding of the present study was that, rather than initial size, vocabulary growth rate from age 4 to age 10 predicted the structure of the AF at age 14. There is evidence at the behavioral level that the rate of vocabulary growth is an important predictor of later language and reading ability (Rowe et al., 2012; Song et al., 2015). Little is known about the neural mechanism underlying this developmental indicator. The present study showed that the structure of the arcuate fasciculus might be an important neural mediator. Together with Asaridou et al.'s (2017) study, the present study highlights the link between vocabulary growth rate and structural brain development. Notably, although both Asaridou et al. and the current study reported the predictive power of vocabulary growth rate, the time range was different. Asaridou et al. focused on vocabulary development before school, while we followed children's vocabulary from preschool to 5th grade. Vocabulary development of infants is more reflective of the family environment and parent–child interactions at home, while vocabulary development after entering primary school may reflect more formal schooling and children's own initiatives in language learning. Furthermore, the brain measures differ between the two studies, so direct comparison is very limited.

Is the relationship between vocabulary growth rate and AF specific to vocabulary? Indeed, it is difficult to disentangle the vocabulary learning experience from reading learning experience, as these two processes overlap and correlate tightly during the school-age years (Nation & Coady, 1988). By statistically controlling the effect of reading development concurrently with vocabulary development, the present study suggested that the relationship between vocabulary development and the arcuate fasciculus is quite specific. This may reflect the fact that reading and vocabulary development involve partly different structures. The long-term development of vocabulary relies on consistent manipulation and articulation of the incoming phonological information. According to the framework of the dual-stream model of language, the dorsal stream (consisting mainly of the AF-direct) is responsible for mapping auditory speech sounds to articulatory representations (Hickok & Poeppel, 2000, 2004, 2007). The specific correlation between vocabulary development and the AF can therefore be taken as supporting evidence for the dorsal pathway in the dual-stream model.

4.5 | Brain lateralization and its relation with language development

Structural asymmetry is a prominent feature of the neural basis for human language. In the present study, we characterized the distribution of the FA lateralization in the direct, anterior and posterior segments of the AF in a normal children sample, and we examined how language development influences FA lateralization. In general, we found that the AF-direct was left lateralized while the AF-anterior was right lateralized. This is consistent with the patterns reported in previous studies in both children (Broce et al., 2015; Eluvathingal et al., 2007; Zhao et al., 2016) and adults (Thiebaut de Schotten et al., 2011). Regarding the AF-posterior, we found significant left asymmetry of this tract, consistent with a previous study (Broce et al., 2015), although other studies did not report any evidence of laterality for this tract (Eluvathingal et al., 2007; Thiebaut de Schotten et al., 2011). Taken together, these findings suggest that there may be greater individual variability across samples for the AF-posterior, possibly in the case of the present study due to the age range and the language background of the Chinese children sample.

It is also noteworthy that FA lateralization of the arcuate fasciculus is associated with long-term language development. Both the developmental groups and vocabulary growth rate predict the lateralization of the AF-posterior. Previous studies have explored the association between lateralization of the white matter pathways and reading or language ability in healthy adults (Catani et al., 2007) or dyslexics (Vandermosten, Poelmans, Sunaert, Ghesquière, & Wouters, 2013; Zhao et al., 2016). The present study extends this result to the longitudinal trajectory of children's vocabulary development.

5 | CONCLUSION

In the present longitudinal study, different vocabulary growth trajectories from age 4 to age 10 were reflected in different anatomical properties of the left arcuate fasciculus at age 14, especially on the AF-direct and AF-posterior segments. The growth rate, rather than the initial size of the vocabulary development further predicted the microstructure of the left arcuate fasciculus. This study suggests that long-term language learning experience from preschool to school-age years might shape the structural development of the adolescent brain.

ACKNOWLEDGEMENTS

We thank all the children and their families for their collaboration in this study. We also thank Zhichao Xia for his help in the MRI data collection, Allyson Covello for the manual correction of the tract dissection. This study was supported by the National Key Basic Research Program of China (2014CB846103), the Key Project of Philosophical and Social Science Foundation, Ministry of Education (11JZD041), the National Natural Science Foundation of China (31271082, 31500886, 31671126), the Fundamental Research Funds for the Central Universities (2017XTCX04), Grant #CUHK8/CRF/13G, the Interdiscipline Research Funds of Beijing Normal University, the Agence Nationale de la Recherche (ANR-11-BSV4-014-01, ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02

PSL*), the China Scholarship Council, the China Postdoctoral Science Foundation Funded Project (2016M591098), and the NSFC-CNRS Joint Research Project Grant (31611130107).

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Su M, Thiebaut de Schotten M, Zhao J, et al. Vocabulary growth rate from preschool to school-age years is reflected in the connectivity of the arcuate fasciculus in 14-year-old children. *Dev Sci*. 2018;21:e12647. https://doi.org/10.1111/desc.12647