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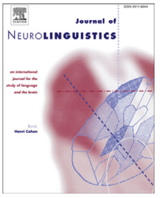

White-matter structure in the right hemisphere predicts Mandarin Chinese learning success

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ABSTRACT

Second language learning becomes increasingly difficult with age, but some adults learn more successfully than others. We examined whether inter-subject variability in the microstructure of white matter pathways, as measured by diffusion tensor imaging (DTI), would predict native English speakers' outcomes in learning Mandarin Chinese. Twenty-one adults were scanned before participating in an intensive 4-week Mandarin course. At the end of the Mandarin course, participants completed a final exam that assessed their skills in both spoken and written Mandarin. Individual participants' white-matter tracts were reconstructed from their native DTI data and related to final-exam performance. Superior language learning was correlated with DTI measures in the right hemisphere, but not in the left hemisphere. In particular, greater initial fractional anisotropy (FA) in both the right superior longitudinal fasciculus (parietal bundle) and the right inferior longitudinal fasciculus was associated with more successful Mandarin learning. The relation between white-matter structure in the right hemisphere of native English speakers and successful initial language learning may reflect the tonal and visuo-spatial properties, respectively, of spoken and written Mandarin Chinese.

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1. Introduction

In contrast to native language acquisition, which seems to be effortless during the first years of childhood, second language acquisition during adulthood is exceptionally challenging (Hull & Vaid, 2007; Johnson & Newport, 1989; Kuhl, 2004; Perani et al., 1998, pp. 1841–1852; Sakai, 2005). Adults vary substantially in their second-language learning efficacy, with few learners achieving native-like fluency in either the spoken or written form of the new language. Little is known about how adult language learning capacities are represented in the brain, but neuroimaging studies have started to explore the structural and functional neural differences underlying individual variation in adult language learning. Here, we asked whether structural differences in white-matter pathways are related to differences among English-speaking adults in learning spoken and written Mandarin.

In studies of English and other alphabetic languages, two white-matter tracts have been most strongly associated with language: the left arcuate fasciculus (AF) component of the superior longitudinal fasciculus (SLF) and the left inferior longitudinal fasciculus (ILF). The SLF connects a dorsal language network (Hickok & Poeppel, 2004, 2007) and is thought to consist of a direct AF pathway connecting posterior (superior temporal gyrus/Wernicke's area) and anterior (inferior frontal gyrus/Broca's area) language cortices and an indirect pathway including the SLFp connecting the inferior parietal cortex and anterior language cortices (Catani, Jones, & Ffytche, 2005). The ILF connects a ventral language network that includes Broca's area and posterior occipitotemporal regions and, via another pathway, the anterior temporal lobe with the uncinate fasciculus (Anwander, Tittgemeyer, von Cramon, Friederici, & Knösche, 2007).

Among these language-related white-matter tracts, the left AF is most prominently implicated in language function; disruption of the left AF leads to impairment in speech production, auditory comprehension, and reading (Dronkers, Plaisant, Iba-Zizen, & Cabanis, 2007; Rauschecker et al., 2009; Vandermosten et al., 2012; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012; Yeatman et al., 2011). The left ILF has also been implicated more specifically in visual (orthographic) aspects of reading, perhaps by transmitting visual information about words between the fusiform gyrus at the temporal-occipital junction and anterior/interior temporal regions (Epelbaum et al., 2008; Yeatman et al., 2012).

Neuroimaging in relation to language learning has shown an association between individual learning performance and both structural and functional connectivity in the left hemisphere. In one study, diffusion measures of the left AF strongly associated with superior learning of English pseudowords (López-Barroso et al., 2013). Another study found a positive correlation between diffusion measures of the left ILF and the learning of associations between Mandarin tones and English pseudowords (Wong, Chandrasekaran, Garibaldi, & Wong, 2011). A resting-state functional magnetic resonance imaging (rsfMRI) study found that successful learning of foreign sound contrasts was associated with greater functional connectivity between Broca's area and the left superior parietal area, which are two regions connected by the left SLFp, a white matter tract in the dorsal pathway (Ventura-Campos et al., 2013). Bilingualism also affects the left inferior frontal-occipital fasciculus, an arguably indistinguishable tract from the left ILF (Wakana et al., 2007), such that fractional anisotropy (FA), one of the diffusivity measures indexing white matter microstructure, is highest in early bilinguals and lowest in monolinguals with late bilinguals being in between (Mohades et al., 2012).

In contrast to the attention given to the left hemisphere, only a few studies have explored relations between structural or functional connectivity in the right hemisphere and language learning, and even these studies have reported mixed findings. One study found diffusion measures in the right AF correlated with individual's performance in pitch-related grammar learning (Loui, Li, & Schlaug, 2011). Conversely, a study of Japanese speakers learning English found no association between the learning performance and the white-matter structure in either the left or right hemisphere before learning. Instead, learning proficiency correlated with the training-induced increases in the strength of the structural connectivity between the right inferior frontal gyrus and caudate (Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013).

Because Mandarin differs from English and other alphabetic languages in both spoken and written forms, the neural bases that support learning Mandarin may be different from those that support learning European (alphabetic) languages. For spoken language, Mandarin has four lexical tones (high-level, rising, dipping and falling) that confer prosodic features to speech at the syllable level. Together with the consonant–vowel combination, lexical tone is a crucial phonetic component signaling the semantics of the syllable. The four tones can be distinguished by the shapes of the internal pitch contour, and there is evidence that the right hemisphere is dominant in processing pitch-related acoustic information (see review: Wong, 2002). Damage to the right auditory cortex or disruptions to its connectivity pattern leads to impairment in pitch-related processing, including production and perception of speech prosody (Baum & Pell, 1999; Loui, Alsop, & Schlaug, 2009; Pell, 1998; Warrier & Zatorre, 2004). Further, the processing of pitch information in speech has been associated with increased activation in both the right superior temporal gyrus and the right inferior frontal gyrus (Meyer, Alter, Friederici, Lohmann, & von Cramon, 2002; Wildgruber, Pihan, Ackermann, Erb, & Grodd, 2002; Zatorre & Gandour, 2008). Thus, the role of pitch perception in spoken Mandarin may invoke greater right-hemisphere participation than that occurring for non-tonal languages.

Despite the role of the right-hemisphere in acoustic processing of lexical tones that is important for spoken Mandarin, there is evidence that phonological processing of lexical tones is subserved by the left hemisphere in native Mandarin speakers (Gandour et al., 2004; Gu, Zhang, Hu, & Zhao, 2013; Tracy et al., 2011; Wang, Wang, & Chen, 2013; Xu et al., 2006). Electrophysiological and fMRI evidence has shown that processing lexical tones is left-lateralized in native Mandarin speakers, especially for pitch contour information, while processing acoustic tones remains right-lateralized regardless of listeners' language background (Gandour et al., 2004; Tong et al., 2005). Thus, there are two alternative possibilities in regards to the lateralization of early learning for naïve Mandarin learners whose native language is English. Early learning of spoken Mandarin could depend upon right-hemisphere networks involved in pitch processing. Alternatively, learning Mandarin lexical tones, which is dominated by the left hemisphere in native Mandarin speakers, may also depend upon left-hemisphere networks.

For written language, Mandarin employs a logographic system. Unlike alphabetic languages, which map visual symbols onto phonemes, each Chinese character is a monosyllabic word. Chinese characters usually consist of two or more spatially arranged radicles with a large variety of spatial relationships. The pronunciation of characters is usually opaque with only 28% of the phonetic radicles carrying the same phoneme information as the whole character (Perfetti, Liu, & Tan, 2005). Thus, Mandarin learners cannot apply the same grapheme-to-phoneme scheme of alphabetic systems while reading Chinese, but instead access the phonological information through visuo-orthographic information of the character (Tan, Hoosain, & Peng, 1995; Tan, Laird, Li, & Fox, 2005). Despite widespread consensus on left-hemisphere dominance in reading (Cohen & Dehaene, 2004; Pugh et al., 2001; Saygin et al., 2013; Tan et al., 2011; Yeatman et al., 2012), a number of cross-linguistic studies have reported language-specific effects on the recruited neural network. Chinese readers showed greater activation of the right middle occipital and right fusiform regions than English readers when reading in their native languages (Bolger, Perfetti, & Schneider, 2005; Tan et al., 2005). In Chinese-English bilingual readers, processing Chinese characters with increased spacing between strokes elicited bilateral activation in the cuneus, while processing English words with increased spacing did not (Sun, Yang, Desroches, Liu, & Peng, 2011). Therefore, we hypothesized that the visuo-spatial demands of learning Chinese characters may invoke right-hemisphere networks specialized for visuo-spatial processing (Pisella et al., 2011).

One DTI study directly examined Mandarin-learning induced change in white matter structure. This longitudinal study measured white-matter microstructure over the course of nine months of Mandarin instruction and found increased fractional anisotropy (FA) in frontal-lobe tracts crossing the genu of the corpus callosum in the language-training group but not in the control group (Schlegel, Rudelson, & Tse, 2012). The development of stronger inter-hemispheric connectivity suggested that Mandarin training in native English speakers, in whom speech and reading is highly left-lateralized, might lead to increased right-hemisphere involvement. This study did not examine whether initial variability in white-matter pathways was associated with better or worse learning.

In the present study, we examined whether the characteristics of language-relevant white-matter pathways (left and right AF, SLFp, and ILF) at baseline were correlated with variation in proficiency of learning spoken and written Mandarin in adults. Learners were students enrolled in an intensive one-month Mandarin training program in the classroom, a traditional learning environment similar to real-life learning experiences. Using diffusion tensor imaging (DTI), we extracted diffusion measures of fractional anisotropy (FA) for each tract within each individual. Because previous research has reported positive correlations between FA values and superior language learning, we hypothesized that higher FA values would predict greater Mandarin proficiency in the learners. In particular, if individual sensitivity to pitch information and visuo-spatial information is important for early Mandarin learning, the right-hemisphere pathways may be more associated with gaining early Mandarin proficiency than the left-hemisphere pathways.

2. Methods

2.1. Language training procedure and proficiency tests

Participants signed up for one of two course sections taught by the same instructor. The course used The New Practical Chinese Reader Volume 1 (Liu, 2010) as the main textbook. The course, which took place on the MIT campus, provided students with intensive training in introductory Modern Standard Mandarin, 3.5 h per day for 5 days per week over 4 weeks. Daily homework was assigned from the companion workbook and was supplemented with additional material designed by the instructor. Throughout the course, participants spent, on average, 62.3 h in the classroom and completed 11 assignments, 10 quizzes, 1 mid-term exam, and 1 final exam. An anonymous mid-term survey (in which 14 of the 21 students responded) showed participants also spent, on average, 2.7 h every day outside of class studying Mandarin.

The final exam was composed of speech production, listening, and reading sections, mostly written in Chinese characters, which tapped into the students' ability to effectively integrate orthographic information with phonologic, semantic, and syntactic information. The final exam was graded by the instructor on a scale of 0–100 and was used as the overall measure for the students' Mandarin learning performance.

In addition to measuring the participants' holistic usage of the language with the final exam total scores, we included two more tests that more specifically measured individuals' phonological skill and orthographic skill. Phonological skill was measured by participants' accuracy in the *pinyin* (an alphabetic phonetic system for Mandarin pronunciation) dictation part of the final exam. The students wrote down the *pinyin* after listening to each of 10 Mandarin phrases/sentences twice. Orthographic skill was measured in a computer-based task at the laboratory administered within one week after the Mandarin course. In each of the 30 trials, participants saw an English word and were asked to choose the correct translation from the two given Chinese characters. All the Chinese characters were taught in the class and were paired based on their close resemblance in visual forms (e.g. STAR, 星or果?). Behavioral accuracy reflected how well one could match the slight difference in the spatial arrangement of strokes with different semantic meanings. For both tests, scores were percentage of correct answers.

2.2. Participants

Twenty-two participants were recruited for the study. Because outlier values can have strong influences on correlational analyses, one participant was excluded based on diffusion measures that deviated more than 2.5 standard deviations from the mean in 5 of the 6 tracts of interest. All analyses proceeded with the remaining twenty-one participants (mean age = 23.6, SD = 3.74; 13 males and 8 females; 18 right-handed and 3 left-handed). All volunteers gave written consent that was approved by the institutional review board at Massachusetts Institute of Technology prior to their participation. Participants were screened for MRI compatibility and no history of neurological diseases. The participants had an average standard IQ of 117 (SD = 12.84) measured by Kaufman Brief Intelligence Test (KBIT-2, Kaufman & Kaufman, 2004). All 21 participants, as indicated by the Language History Questionnaire (Linck et al., 2013), were native American-English speakers, of which 17 were monolinguals with no extensive exposure to languages other than English as a child. Four participants reported growing up in a bilingual environment (Polish, Spanish, Hindi and Hebrew). Among these, three participants spoke the other language fluently and one participant spoke English exclusively during childhood. Importantly, the four bilingual participants did not differ from the monolinguals in respect to their average final exam scores (77.5 vs. 76.8, out of 100). All participants were exposed to foreign languages, ranging from 1 to 5 different languages, with large variability in the level of fluency. The self-report fluency of the second language ranged between 1.0 (limited) and 5.0 (excellent), with an average of 3.0 (standard deviation, 1.15). However, crucially, none of the participants had prior exposure to Chinese, other tonal languages (e.g. Thai), or any other language with a logographic writing system (e.g. Japanese Kanji).

2.3. Imaging acquisition and processing

Diffusion tensor images were acquired before Mandarin training began. Data were collected on a Siemens Trio 3-Tesla MRI scanner with a standard 32-channel phased array head coil (TE = 84 ms; TR = 8040 ms). The diffusion-weighted scan included 10 non-diffusion-weighted reference volumes ($b = 0$) and 60 diffusion-weighted volumes ($b = 700$ s/mm2) with voxel resolution of 2.0 mm isotropic (field of view = 256 mm; matrix = 128 mm × 128 mm) and 64 slices per volume. The b0 volumes were collected in the first 10 volumes of the entire scan and were later averaged. A high-resolution T1-weighted magnetization prepared rapid gradient echo (MPRAGE) scan was also acquired (TE = 1.64 ms; TR = 2530 ms; FOV = 220 mm; matrix = 220 mm × 220 mm; 176 slices). Cortical and white matter surfaces were generated according to individual landmarks using the FreeSurfer image analysis suite (http://surfer.nmr.mgh.harvard.edu/), with further manual editing for accuracy.

The DTI data were pre-processed using DTIPrep's (Oguz et al., 2014) automated artifact detection software, which automatically excluded extensively distorted volumes. The data were then processed using TRACULA (Yendiki et al., 2011), which corrected for eddy currents and head motion; performed both intra- and inter-registration of each subject's b0 diffusion images to their T1-weighted images and the MNI template respectively; calculated the tensor fit at each voxel to generate maps of diffusion tensor eigenvalues; and estimated the endpoints and waypoints for each major white matter pathway using subject-specific anatomical information. FSL's bedpostx tool was used to fit a ball-and-stick model of diffusion to each subject's DWIs. TRACULA's pathway reconstruction software generated probability distributions of the trajectory of the 18 major white matter pathways. Of these, we examined three bilateral tracts of interest, defined *a priori*: the ILF, the SLFp, and the AF (Fig. 1).

The diffusion tensor eigenvalues extracted from TRACULA outputs were used to compute axial diffusivity (AD), radial diffusivity (RD), and fractional anisotropy (FA) for the three bilateral tracts of interest. AD describes diffusion along the longest principal axis of a fiber. RD describes diffusion perpendicular to the principle diffusion direction. FA describes the ratio of normalized standard deviation and root mean square of the three diffusion directions. The FA values range from 0 (equal diffusion in all directions) to 1, with FA values of 0.2–1 indicating white matter and greater values connoting greater white matter integrity (Kunimatsu et al., 2004). In our analysis, FA was used as the main measure because it summarizes white matter microstructure. AD and RD values were used in a

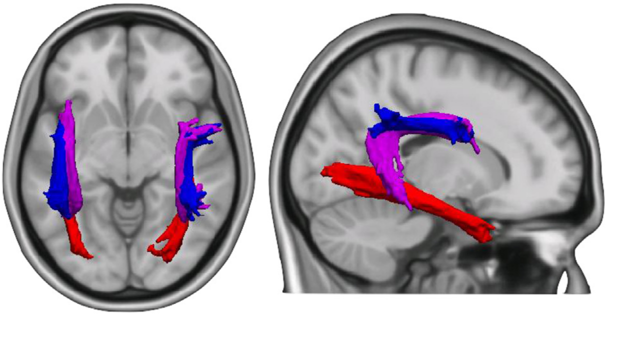

Fig. 1. Illustration of tracts of interest in axial (left) and sagittal (right) views. Tracts were extracted from an example subject and were registered to Montreal Neurological Imaging (MNI) template space. The tracts of interest include: Inferior Longitudinal Fasciculus (ILF, red); Superior Longitudinal Fasciculus parietal bundle (SLFp, blue) and Arcuate Fasciculus (AF, purple).

post hoc analysis after we located tracts that were important for Mandarin learning, in order to better characterize the underlying biological factors contributing to the inter-subject variability of the FA values.

2.4. Statistical methods

We examined the relations between the participants' final exam scores and three measures derived from the FA values: 1) average FA across all three tracts of interest within each hemisphere; 2) average FA within each tract of interest; and 3) laterality scores of each pair of tracts calculated as Laterality Score $= (FA_{left} - FA_{right})/(FA_{left} + FA_{right})$. More positive laterality scores indicate higher average FA values in the left tract, i.e. left-lateralized. More negative laterality scores indicate higher average FA values in the right tract, i.e. right-lateralized. Because FA values are bounded between 0 and 1 with considerable skew and kurtosis (Alexander, Lee, Lazar, & Field, 2007), data normality was not assumed. Therefore, for all the following analyses, we adopted a non-parametric method, Spearman's rank correlation. All reported p values have been false detection rate (FDR) corrected for multiple comparisons (FDR < 0.05).

For analyses with unidirectional hypotheses (greater FA in the tracts for analysis are associated with better learning performance), one-tailed statistical tests were used. For analyses where both directions of hypothesis were possible (correlation between tract lateralization and learning performance), two-tailed tests were used.

3. Results

3.1. Right but not left hemisphere tracts predicted Mandarin learning ability

The mean baseline FA of the three left-hemisphere tracts did not significantly correlate with final exam scores (Spearman's $\rho = .24$, one-tailed $p = .14$; Fig. 2a), but there was a significant correlation between the mean baseline FA of the three right-hemisphere tracts and final exam scores (Spearman's $\rho = .55$, one-tailed $p = .005$; Fig. 2b). The selective correlation with right-hemisphere pathways occurred despite strong overall correlations between the means of the left and right pathways across individuals (Spearman's $\rho = .65$, two-tailed $p = .001$). We directly compared the strengths of the left- and right-hemisphere correlations using a bootstrap procedure, which generated a confidence interval based on 10^5 random resamplings in order to test whether they were statistically different

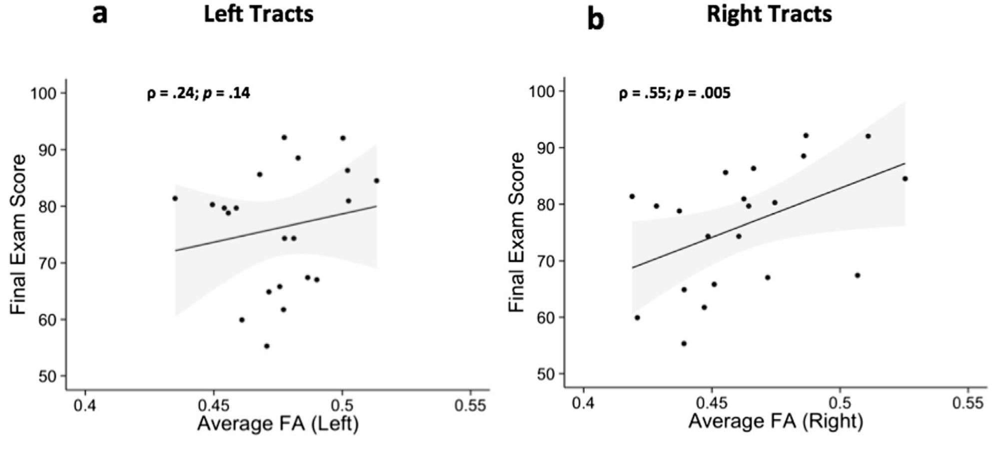

Fig. 2. Correlation between the average FA across three tracts of interest (ILF, SLFp and AF) and final exam scores. The average FA value of (a) the left tracts did not correlate with subsequent Mandarin learning success, while the average FA value of (b) the right tracts did correlate significantly and positively with subsequent Mandarin learning success. Black lines represent the linear trend of the correlation and grey shades represent the 95% confidence interval of the data.

from each other (DiCiccio & Efron, 1996). There was a significantly stronger correlation between the final exam scores and FA values in the right hemisphere than those in the left hemisphere (one-tailed $p < .02$).

3.2. Right ILF and right SLFp predicted Mandarin learning ability

Individual final exam scores correlated positively with FA of the right ILF (Spearman's $\rho = .50$, one-tailed FDR-corrected, $p = .03$; Fig. 3a) and the right SLFp (Spearman's $\rho = .60$, one-tailed FDR-corrected, $p = .01$; Fig. 3b). Because final exam scores were also marginally correlated with IQ (Spearman's $\rho = .32$, one-tailed $p = .08$), we conducted a partial correlation analysis to control for individual IQ. The correlation between final exam scores and FA of both tracts remained significant (p's < .02). Individual IQ scores and tract FA values (arcsin transformed in order to meet the normality assumption of the linear regression analyses) were fit into linear regression models for the prediction of the final exam scores. Compared with the model using IQ as the only predictor, adding either right SLFp or right ILF FA values as a second predictor increased the variance of data explained by the model from 15.1% to 25.1% and 22.4%, respectively (model comparison $p = .04$; $p = .06$). There were also marginally significant correlations between the FA values in the left AF, right AF, and left ILF and participants' final exam scores (uncorrected p's < .10, Table 1).

In order to further investigate the possible anatomical structure differences that contributed to the inter-subject variability of FA values, we analyzed two additional diffusion parameters, AD and RD, in the right ILF and right SLFp. The average AD did not correlate with individual final exam scores in either tract (Spearman's ρ's < .06, one-tailed p's > .28). However, the average RD significantly correlated with

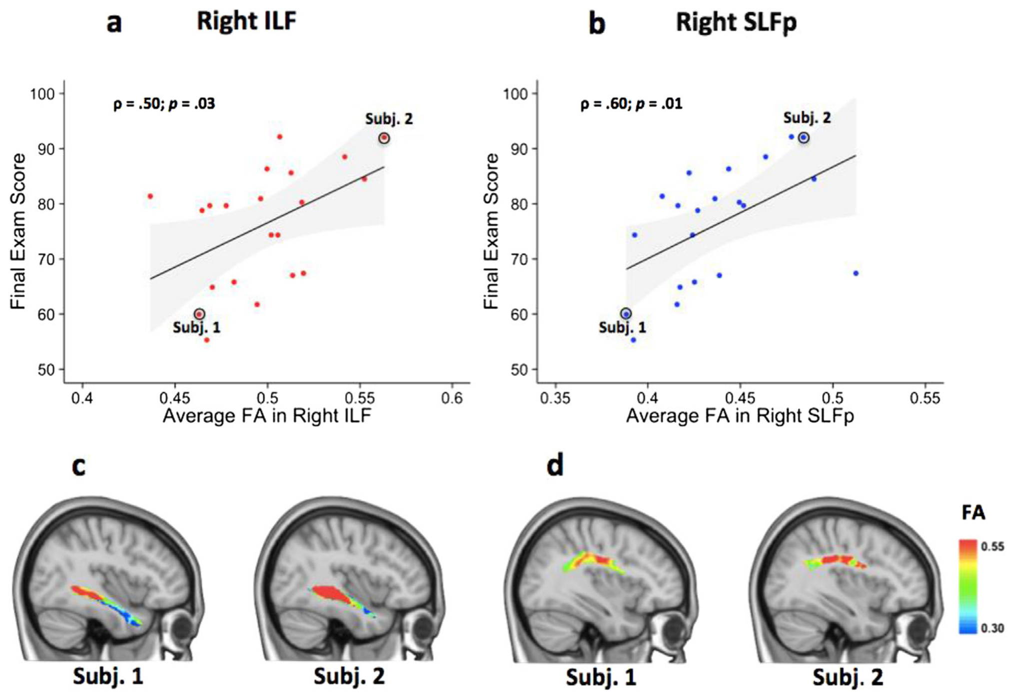

Fig. 3. Greater initial FA values of (a) the right ILF and (b) the right SLFp correlate with subsequent Mandarin learning success. In both (a) and (b), black lines represent the linear trend of the correlation and grey shades represent the 95% confidence interval of the data. (c) Right ILF and (d) right SLFp were rendered in two example subjects (circled points) to illustrate the FA difference between a less successful (Subj. 1) and a more successful (Subj. 2) learner. The tracts are colored according to the FA values.

individual final exam score in both the right ILF (Spearman's $\rho = -0.56$, one-tailed $p = 0.005$) and the right SLFp (Spearman's $\rho = -0.57$, one-tailed $p = 0.004$).

We also examined the specific relations of the right ILF and SLFp tracts to Mandarin phonology learning (as measured by the *pinyin* dictation task in the final exam) and orthography learning (as measured by the two-alternative forced-choice task). Participants' performance on the final phonology measure correlated significantly with baseline average FA values of both the right ILF (Spearman's $\rho = 0.42$, one-tailed $p = 0.03$) and the right SLFp (Spearman's $\rho = 0.45$, one-tailed $p = 0.02$). Participants' performance on the final orthography measure, however, correlated significantly only with the average FA values of the right ILF (Spearman's $\rho = 0.54$, one-tailed $p = 0.006$) and not the right SLFp (Spearman's $\rho = 0.21$, one-tailed $p = 0.18$).

3.3. *Laterality of ILF and SLFp predicted Mandarin learning ability*

Given that right-hemisphere tracts played a greater role in predicting Mandarin learning efficacy than left-hemisphere tracts, we further examined the relation between hemispheric asymmetry of white-matter microstructure and Mandarin learning performance. By comparing the FA values between the two hemispheres for each pair of tracts of interest, we calculated laterality scores for each tract in each participant. Participants displayed great variability in lateralization. More than 50% of the participants showed right-lateralized ILF, whereas more than 50% showed left-lateralized SLFp (Fig. 4). Greater right-lateralization of ILF FA correlated positively with superior final exam scores (Spearman's $\rho = -.53$, two-tailed FDR-corrected $p = .04$; Fig. 4a) and greater right-lateralization of SLFp FA tended to correlate with superior final exam scores (Spearman's $\rho = -.45$, two-tailed FDR-corrected $p = .06$; Fig. 4b). There was no relation between final exam scores and AF lateralization (Spearman's $\rho = -.16$, two-tailed FDR-corrected $p = .49$).

4. Discussion

In this study, we investigated the relations between initial white-matter microstructure and subsequent Mandarin learning success. Native English speakers enrolled in a one-month introductory Mandarin course and reached a wide range of proficiency at the end of the training. We found a significantly stronger positive correlation between students' final exam scores and initial FA in right-hemisphere tracts than in left-hemisphere tracts. In particular, higher FA in the right ILF and right SLFp predicted greater success in learning Mandarin. As revealed by separate behavioral subtests, FA in both right-hemisphere tracts was associated with phonology learning success, while FA in the right ILF was associated with only orthography learning success. Analysis of hemispheric asymmetries of FA further revealed that more rightward ILF and less leftward SLFp were associated with higher final exam scores. These results provide converging evidence for the hypothesis that the right-hemisphere tracts play a more important role than left hemisphere tracts in preparing adults for initial learning of Mandarin as a second language.

4.1. *Tract laterality and handedness*

The FA characterization of white-matter tracts is consistent with other studies. Previous research, like our study, has shown that FA in homologous white matter structures are highly correlated in individuals (Wahl et al., 2010). Our laterality analysis of tract FA values showed left-lateralized SLF tracts

Table 1
Spearman correlations between white matter anisotropy and the final exam score.

	Left ILF	*Left SLFp*	*Left* AF	Right ILF	Right SLFp	Right AF
Correlation	.29	.05	.35	**.50**	**.60**	.32
p (Uncorrected)	.10	.41	.06	**.01**	**.002**	.08
p (FDR)	.12	.51	.12	**.03**	**.01**	.12

FDR = false-discovery rate; Numbers in bold fonts indicate statistical significance.

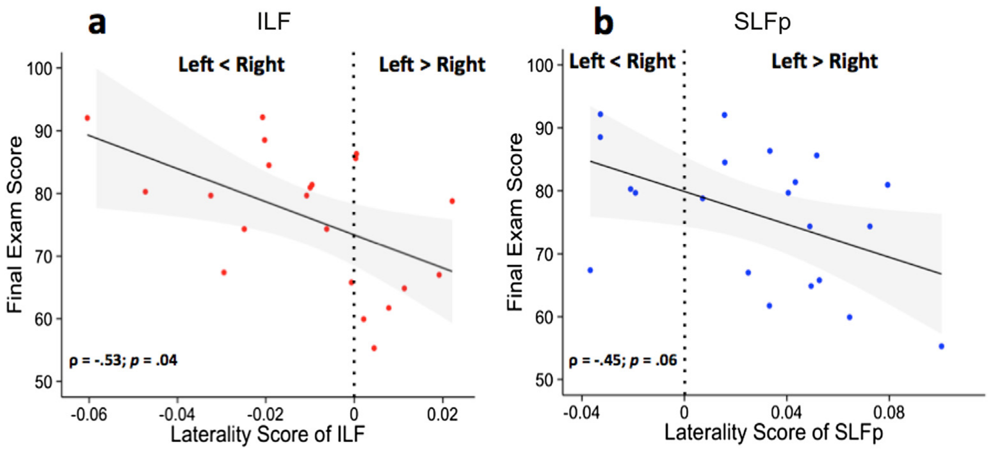

Fig. 4. Initial hemispheric asymmetry of tract FA values correlates with subsequent Mandarin learning success. (a) More right-lateralized ILF and (b) less left-lateralized SLFp were associated with higher final exam scores. Black lines represent the linear trend of the correlation and grey shades represent the 95% confidence interval of the data.

in most participants, consistent with findings of volume asymmetry of the tracts (Ellmore et al., 2010; Glasser & Rilling, 2008; Saur et al., 2010). Because the incidence of right functional laterality in language increases with the degree of left-handedness (Basic et al., 2004; Lorenz et al., 2008), one possible concern regarding the current data set is that our sample included three left-handers. However, the tract laterality scores of all three left-handers showed left lateralized SLFp, similar to the majority of the right-handers. We also reanalyzed the data excluding the three left-handers and found the same significant correlations between the right-hemisphere tracts and Mandarin learning. This result is consistent with previous findings of an overall leftward asymmetry of AF regardless of handedness or functional language lateralization, as determined by the hemispheric difference in response to a verb production task (Vernooij et al., 2007).

4.2. DTI analyses of white-matter microstructure

Higher FA values likely reflect a number of different tract-specific properties, including fiber diameter, fiber density, membrane permeability, and myelination (Beaulieu, 2002; Jones, Knösche, & Turner, 2012), which can be associated with higher AD and/or lower RD (Song et al., 2002; Takahashi et al., 2002). Our findings showed it was RD, but not AD, that carried the correlation between the white matter microstructure and Mandarin learning success. This finding suggests that increased axonal myelination or denser axonal tracts (lower RD), rather than axonal integrity measured by AD, supported superior Mandarin learning.

There are limitations to DTI analyses of white-matter tracts. First, diffusion tensor modeling is not able to solve the problem of intra-voxel crossing fibers. Reduced RD and increased FA might result from fewer crossing fibers in successful learners. Therefore, the precise neurobiological basis of the FA correlations cannot be determined. Second, there are limitations to the accurate delineation of tracts by TRACULA. TRACULA reconstructs white matter into 18 tracts, based on the anatomical regions of interest defined in Makris et al. (2005) (Yendiki et al., 2011). The SLF is divided into AF and SLFp. The AF in this study corresponds best to the classically defined “direct” pathway of the arcuate fasciculus, while the SLFp is closest to the anterior segment of the “indirect” pathway (Catani et al., 2005). TRACULA does not, however, differentiate the posterior segment of the indirect pathway from the posterior part of the AF, both of which connect the posterior parietal area with the posterior temporal area. Likewise, TRACULA identifies ILF as one of the ventral stream pathways. It is possible, however that the ILF includes fibers from other language-related ventral pathways, such as the middle longitudinal fasciculus and inferior fronto-occipital fasciculus (Dick & Tremblay, 2012; Saur et al., 2008; Wong et al., 2011).

4.3. Right-hemisphere contribution to Mandarin learning

In the present study, white-matter diffusivity measures in the right hemisphere predicted Mandarin learning. On the surface, these findings may seem to contradict the dominant involvement of left hemisphere tracts in learning new phonemes, words, and grammar in adults (Flöel, de Vries, Scholz, Breitenstein, & Johansen-Berg, 2009; López-Barroso et al., 2013; Wong et al., 2011; see review: Friederici, 2009). Prior studies found associations between diffusivity measures in the left hemisphere, but not in the right hemisphere, and language learning performance. However, those studies focused on European languages without the tonal properties of Mandarin or the non-alphabetic visuo-spatial properties of Chinese characters.

Neuroimaging studies have found evidence suggesting that the brain areas connected by the ILF and the SLFp in the right hemisphere participate in processing pitch information of Mandarin speech. In a Chinese character naming task, native Mandarin speakers recruited the right inferior frontal gyrus more strongly in the production of characters with different tones than the production of characters with different vowels (Liu et al., 2006). Moreover, the engagement of the right hemisphere in early attention to pitch information in Mandarin appears to be a shared mechanism irrespective of language experience. A rightward asymmetry of activation in the superior temporal sulcus and the middle frontal gyrus was found in both Mandarin and English native speakers performing same-different judgment on Mandarin intonation across syllables and on tones within syllables (Gandour et al., 2004). Similarly, a rightward asymmetry in the middle frontal gyrus was reported in both Mandarin and English native speakers processing sentence-level prosody of Mandarin (Tong et al., 2005). The most relevant evidence comes from a training study in native English speakers who were naïve to Mandarin. The level of activation in the right temporal gyrus, as well as the left temporal gyrus, during a tone discrimination task predicted whether an individual was successful in learning new pseudowords with Mandarin lexical tones (Wong, Perrachione, & Parrish, 2007).

White-matter studies provide evidence for a structural counterpart to the right-hemisphere functional specialization for pitch processing. A DTI-identified pathway between superior/middle temporal gyrus and the frontal lobe is located in right-hemisphere regions associated with prosodic processing in European languages (Glasser & Rilling, 2008). The reduction of right SLF volume was found to be associated with the behavioral deficiencies of tone-deafness (Loui et al., 2009). Moreover, there was a positive correlation between FA of the right temporal-parietal conjunction and individual's ability to learn an artificial pitch-related grammar (Loui et al., 2011). Further, cross-sectional studies discovered right-hemisphere structural characteristics specific to Chinese speakers. Higher FA in the right superior temporal and the right lingual gyrus white-matter regions were positively correlated with faster reading time of English words in a Chinese-English bilingual group, but not in an English monolingual group (Cummine & Boliek, 2013). Increased white-matter volume in the tract arising from the right Heschl's gyrus was found in multilingual Mandarin speakers and native Mandarin speakers, but not in European multilinguals who did not speak Mandarin (Crinion et al., 2009). Overall, these studies support the idea that due to the tonal nature of Mandarin speech, there is greater right-hemisphere involvement for Mandarin speech than for non-tonal European languages.

The other challenge Mandarin learners usually face is learning to read Chinese characters, which have great visuo-spatial complexity. Previous studies showed greater activation of the right middle occipital and right fusiform regions in Chinese readers than English readers when reading in their native languages (Bolger et al., 2005; Tan et al., 2005). English speakers learning Mandarin increased recruitment of the right fusiform regions when viewing Chinese characters (Nelson, Liu, Fiez, & Perfetti, 2009). Our finding that learners' performance in the orthography task positively associated with their FA values of the right ILF tract before training is consistent with these findings. It is noteworthy that only the properties of the right ILF, which is associated with visual processes, and not the right SLFp, which is more associated with auditory processes, had a significant association with orthography learning in Mandarin Chinese. In Mandarin, semantic analysis of Chinese characters is difficult via phonology because there is a lack of transparent mapping between phonemes and graphemes, and there are many homophones per single-syllable word. Therefore, direct mapping of orthographic information to meaning may be efficient, especially in early learning. The correlation of the right ILF, but not the right SLFp, with superior orthographic learning is consistent with the idea that early learning of Chinese characters is more related to visual and less to phonological processes than that occurs in alphabetic languages.

Neuropsychological evidence also supports the possibility that learning tonal and visuo-spatial aspects of Mandarin may invoke right-hemisphere brain regions. Damage to the right auditory cortex leads to impairment in pitch-related calculation, including production and perception of speech prosody (Baum & Pell, 1999; Loui et al., 2009; Pell, 1998; Warrier & Zatorre, 2004). Lesion at the right posterior parietal regions and occipital regions leads to disruption of visuo-spatial attention network (Halligan, Fink, Marshall, & Vallar, 2003; Mosidze, Mkheidze, & Makashvili, 1994; Pisella et al., 2011). Both the right dorsal and ventral visual streams have been implicated to play important roles in the cognitive control of visual search (Lane, Groisman, & Ferreira, 2006).

An alternative interpretation of our finding is that the microstructure of white matter in the right hemisphere is involved not only in Mandarin learning, but also second-language learning in general. A behavioral meta-analyses study of bilingual laterality found that second language proficiency in late bilinguals was positively correlated with right-hemisphere involvement (Hull & Vaid, 2007). The extent of right-hemisphere involvement appears to be modulated by the similarity between L1 and L2. A dichotic behavioral test with English words as L2 showed reduced leftward asymmetry in Italian speakers, whose native language is less similar to English compared to German speakers (D'Anselmo, Reiterer, Zuccarini, Tommasi, & Brancucci, 2013).

The contribution of right hemisphere in bilingualism is further supported by a number of neuroimaging studies. An fMRI study revealed more bilateral activation elicited by children who processed English speech as a second language compared to those who processed English speech as a native language (Archila-Suerte, Zevin, Ramos, & Hernandez, 2013). Similar findings from a MEG study suggested greater right visual word form area activation and therefore more bilateral recruitment in L2 (English) word processing compared to L1 (Spanish, Leonard et al., 2010). Structural MRI studies found that increased exposure to second language is associated with greater grey matter density in the right hippocampus (Mårtensson et al., 2012). Compared to monolingual English speakers, early bilingual speakers of two alphabetical languages showed stronger anterior-posterior structural and functional connectivity within both the left and right hemispheres (Luk, Bialystok, Craik, & Grady, 2011). Early bilingual speakers also showed increased structural connectivity in a subnetwork involving the right superior frontal gyrus and the left reading network measured by graph efficiency (García-Pentón, Pérez Fernández, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014). One longitudinal study revealed learning-induced change of right-hemisphere structure within individuals. Japanese speakers showed enhancement of grey matter and white matter density in the right IFG after learning English (Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013).

Together, these studies suggest right-hemisphere involvement in second-language learning may not be limited to Mandarin learning. The cognitive control demands of adapting to new linguistic rules, as well as selecting, switching, and translating between native and foreign languages might lead to recruiting areas outside of the network for one's native language, such as bilateral prefrontal and parietal areas (Abutalebi & Green, 2007; Li, Legault & Litcofsky, 2014; Luk & Green, 2011). The present study is not able to differentiate between these two alternative explanations. Only an experiment with another control group of participants learning an alphabetic language could test the specific role of the right hemisphere in Mandarin learning.

Finally, it is noteworthy that the association between white matter structure and Mandarin learning success revealed in the current study is based on the proficiency tests after only one month of training. Language learning at a more advanced stage may involve distinct underlying processes from earlier stages, and therefore may show a different relationship with brain structure. The importance of left-hemisphere engagement in fluent Mandarin has been implicated by the findings that native Mandarin speakers show left-lateralized functional representation of language (Gandour et al., 2004; Hsieh, Gandour, Wong, & Hutchins, 2001; Klein, Zatorre, Milner, & Zhao, 2001; Tong et al., 2005; Xu et al., 2006). Thus, left-hemisphere networks and tracts may become increasingly important as learners' proficiency improves. More studies are necessary to unveil the complete picture of the neurobiology of second language learning.

5. Conclusion

It has long been noted that adult learners of a second language often achieve quite different levels of proficiency. The current study presented a right-lateralized association between white-matter microstructure and successful Mandarin learning, with higher FA in the right SLFp and right ILF predicting superior learning in a real language-learning environment. Our results also indicated a greater contribution of right hemisphere than left hemisphere in successful Mandarin learning in the initial phase of acquisition.

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