Reading skill and related neural pathways in adult bilinguals

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Reading skill and neural pathways in bilinguals

Abstract

This study examined the structural integrity of white matter tracts related to reading in twelve Chinese-English adult bilinguals. Participants read aloud three lists of words varying in their proportions of regular (REG) and exception (EXC) words as quickly and accurately as possible. Using diffusion tensor imaging (DTI) and tractography analysis, measures of white matter integrity, namely fractional anisotropy (FA) and mean diffusivity (MD), were examined against the behavioural measures of accuracy (ACC) and response time (RT). With a dual-route model of reading in mind, ventral tracts examined included the uncinate fasciculus (UF), inferior fronto-occipital fasciculus (IFOF), and the inferior longitudinal fasciculus (ILF). The dorsal tracts of interest were the arcuate fasciculus (AF) and the superior longitudinal fasciculus (SLF). Each of the tracts of interest was isolated in both the left and right hemispheres. The mid-superior portion of the fornix was used as a control. Results revealed significant correlations between behavioural measures (RT and ACC) and FA in the right UF, and MD in the right AF and bilaterally in the SLF. These findings support the notion of a role of the right hemisphere in reading, in both dorsal and ventral pathways.

INTRODUCTION

From e-mails to text messages, written communication holds an increasingly important role in today's society. Given this increased reliance, one can imagine the devastating impact of reading impairments in daily communication. Thus far, much work has been done on the functional framework of reading (Binder et al., 2009; Borowsky et al., 2006; Borowsky et al., 2007; Cohen & Dehaene, 2009; Cohen et al., 2008; Hickok, 2009; Hickok & Poeppel, 2004; Levy et al., 2009; Mechelli et al., 2005; Posner & Raichle, 1994; Price, 2010; Pugh et al., 2001). However, few studies have examined a structural framework (Lopez-Barroso et al., 2011; Saur et al., 2008; 2010; Richardson, Price, 2009, & Dai, 2013.). Furthermore, little to no information exists on the underlying neural structural correlates of reading in bilinguals. This study sought to provide heuristically important information about underlying cortical and subcortical white matter structural integrity and its relationship to basic reading processes in adult bilinguals. Such knowledge adds to our understanding of both reading and reading impairments in bilingual populations.

Purpose

The purpose of our research was to investigate the relationship between behavioural measures of reading and structural measures of white matter fibre tracts found in healthy adult Chinese-English bilingual speakers. Behavioural measurements of reaction time and reading accuracy were correlated to measurements of white matter tract integrity including fractional anisotropy (FA) and mean diffusivity (MD) derived from diffusion-tensor magnetic resonance imaging (DTI), and tractography methodology. The following questions were examined;

(1) Does the integrity of white matter tracts in ventral pathways (e.g. uncinate fasciculus) have a positive relationship with stimuli known to activate ventral regions (e.g. exception words)?

(2) Does the integrity of white matter tracts in neural pathways of interest have a positive relationship to reading ability, as determined by accuracy and speed, in sequential bilinguals?

BACKGROUND

Dual language route

Previous neuro-functional and neuro-structural language research supports the distinction between a ventral-lexical-sound-to-meaning pathway extending from occipital-temporal-frontal, and a dorsal-sub-lexical-sound-to-articulation pathway extending from occipital-parietal-frontal (Jobard et al., 2005; Price, 2010). The ventral stream is purported to be a lexically-driven path characterized by whole-word memory recognition for familiar words and exception words (e.g., letter strings with an atypical spelling-to-sound correspondence, *pint*; Steinbrink et al., 2008; Pugh et al., 2000). Thus, this route is used to access familiar words stored in lexical memory (Borowsky et al., 2006). The dorsal stream is characterized as a sub-lexical pathway that integrates orthographic information (graphemes) with their phonological, morphological, and lexical-semantic counterparts (Pugh et al., 2000; Borowsky et al., 2006; Steinbrink et al., 2008). Hence, the dorsal route plays an important role when learning how to read by mapping sound-to-letter correspondence and less familiar regular words (e.g., words with a typical spelling-to-sound correspondence, *hint*; Pugh et al., 2000; Steinbrink et al., 2008; and Borowsky et al., 2006).

The ventral and dorsal streams are associated with different types of word reading. For example, exception words are learned and stored in memory as whole-word units because they do not follow rule-based phonological representations. Thus, the use of the ventral route for exception words is expected. Regular words, on the other hand, follow rule-based phonological representations, therefore the dorsal tract can be used for sounding out a new or unfamiliar word. The ventral tract can then also be used to access lexical meaning after a regular word has been well learned. So, unlike exception words that have to be read via a ventral route, regular words can use both routes for word reading.

Chinese Bilinguals Reading English

The English and Chinese languages have distinct patterns of writing. English has an alphabetical system that can be divided and sequenced, whereas Chinese uses characters to represent whole words (Tan et al., 2003). Tan et al. (2003) suggest that bilingual participants apply their native language systems when reading in a second language. Thus, native Chinese speakers using a whole word approach to reading English may have difficulty because of the inherent letter-to-sound correspondence for many written words. Bialystok, Luk, & Kwan (2005) found that only when languages use the same writing system (e.g. alphabetical or characters) are the reading skills transferred. Their study demonstrated that reading in a second language is a difficult task especially when the writing systems between the two languages are different. In contrast, Chee, Tan & Thiel (1999) compared activation of cortical areas of both Mandarin and English through fMRI and found no significant differences at the single word level when not taking into account age of acquisition.

When looking at Chinese bilinguals it is important to understand their neural mechanisms involved in reading. Kuo et al. (2004) investigated these neural mechanisms involved in the processing of orthographic and phonological information in Chinese using fMRI. They found that the areas involved in orthographic processing were identified as the left occipitotemporal region, left dorsal processing stream, and right middle frontal gyrus (Kuo et al., 2004). Phonological processing took place in the left premotor gyrus, left middle/inferior frontal gyrus, supplementary motor area, and the left temporoparietal region (Kuo et al., 2004). Overall Kuo et al. (2004) found that the dorsal visual stream was activated more in Chinese homophone perception. This corresponds to the strong relationship between the Chinese orthographic understanding and the phonological presentation of Chinese characters.

Another important factor to consider when looking at bilinguals and reading ability is the difference between early and late bilinguals. Chee, Tan & Thiel (1999) looked at differences in early and late bilinguals by comparing prefrontal language areas for peak-location and hemispheric asymmetry. They found a similar system of activations in both early and late acquisition. Expanding on the idea of early and late bilinguals, Mohades et al. (2011) analyzed the differences between sequential and simultaneous bilinguals. They found that simultaneous bilinguals had higher FA in the left inferior occipital frontal fasciculus (Mohades et al. 2011).

Diffusion Tensor Imaging, measures of FA and MD & ROI Analysis

Diffusion tensor imaging (DTI) provides a unique non-invasive neuroimaging method for deriving neural fibre composition and orientation (Beaulieu, 2002). Tractography, a three-dimensional reconstruction derived from DTI, is now a commonly used tool in the study of the anatomy of white matter (Wakana et al., 2007). There is increasing evidence that DTI tractography is reliable and also has been validated using post-mortem studies of white matter tracts (Wakana et al., 2007). However, tractography is also susceptible to falsely identifying tracts because of poor signal to noise, partial volume effects, and complex fibre architecture within a pixel (Pierpaoli et al., 2001; Wiegell et al., 2000, Wakana 2007). A technique in use that can increase validity is to use multiple regions of interest (ROI) to act as anatomical restraints (Conturo et al., 1999; Huang et al., 2004, Wakana et al., 2007). This approach achieves increased reliability only when prior knowledge of the tracts is employed; therefore, it is important to establish a reproducible protocol for each tract (Wakana et al., 2007).

Measures used to assess the integrity of white matter tracts include fractional anisotropy (FA) and mean diffusivity (MD). FA is a measure of the directionality of diffusion with values ranging from zero to one (Beaulieu, 2004.) Higher FA values are indicative of more directional diffusion (Deutsch et al., 2005; Niogi & McCandliss, 2006; Odegard et al., 2009, Beaulieu 2004, Dai, 2013). MD is the mean of the eigenvalues of the diffusion tensor and as such, it reflects the magnitude of diffusion. The MD measure is invariant with respect to the orientation of diffusion tensor and tends to vary little across brain tissue (Shachar et al., 2007). The formulae for the calculation of FA and MD are provided below.

$$\mathrm{FA} = \sqrt{\frac{3}{2}}\frac{\sqrt{(\lambda_1-\hat{\lambda})^2+(\lambda_2-\hat{\lambda})^2+(\lambda_3-\hat{\lambda})^2}}{\sqrt{\lambda_1^2+\lambda_2^2+\lambda_3^2}}$$

$$\text{Where } \hat{\lambda} = (\lambda_1+\lambda_2+\lambda_3)/3$$

$$MD = (\lambda_1+\lambda_2+\lambda_3)/3$$

Tracts

Uncinate Fasciculus. The UF has been theoretically shown to be a significant tract in language processing (Catani & Mesulam, 2008; Papagno et al., 2011; Duffau et al., 2009). Studies have identified that the UF connects the orbitofrontal cortex and the anterior temporal lobe (Catani et al., 2002; Schmahmann et al., 2007). This connection is understood to contribute to lexical retrieval, semantic associations, and aspects of naming (Grossman et al., 2004; Lu et al., 2002). Results from other studies also have demonstrated the role the UF plays in semantic processing (Makris et al., 2005; Mandonnet et al., 2007).

Inferior Fronto-Occipital Fasciculus. Connecting the frontal and occipital cortices through the extreme capsule, the IFOF is a substantial white matter tract (Catani, 2007; Yeatman et al., 2013; Vandermosten et al., 2012). It has been suggested that the IFOF is a part of the ventral processing stream (Vandermosten et al., 2012; Catani & Mesulam, 2008). The IFOF is believed to be involved in reading and writing; although to what extent is not entirely understood (Catani & Mesulam, 2008; Steinbrink et al., 2008). Steinbrink et al. (2008) found a correlation between the FA in white matter regions associated with the IFOF and reading ability. Vandermonsten et al. (2012) also found a relationship between FA in the left IFOF and orthographic processing. Mandonnet et al. (2007) found that when electrically stimulating the IFOF they were able to produce a semantic paraphasia (i.e. the word "chair" is replaced by a different word that is related in meaning "table"). The results from these studies all demonstrate a possible connection between reading ability and the IFOF.

Inferior Longitudinal Fasciculus. The inferior longitudinal fasciculus (ILF) was selected as a tract of interest because it is an important component of the ventral processing stream subserving comprehension (Chandrasekaran et al., 2011; Hickok & Poeppel, 2004; Saur et al., 2008; and Saur et al., 2010). The ILF also is thought to relay visual information from the occipital area to the temporal lobe (Catani et al., 2003). Additionally, a bilingual DTI study by Luk et al. (2011), found higher white matter integrity in the ILF for adult bilinguals, thus revealing a structural difference in the ILF between monolinguals and bilinguals.

Arcuate Fasciculus. For more than a century, the arcuate fasciculus (AF) has been recognized as the white matter tract connecting Wernicke's and Broca's areas, delivering linguistic input (both written and spoken) to cortical output areas. Contemporary findings have suggested that the AF carries signals used for manipulation and articulation of incoming phonological information (Hickok & Poeppel, 2004; Hickok & Poeppel, 2007). More recently still, Yeatman et al. (2011) found that phonological awareness skills correlated with measurements of diffusivity in the left AF, and phonological memory and reading skills correlate with arcuate volume lateralization.

Superior Longitudinal Fasciculus. The Superior Longitudinal Fasciculus (SLF) is a major anterior-posterior cortical association pathway, connecting perisylvian frontal, parietal, and temporal association areas (Wakana et al. 2004; Makris et al., 2005; Gold et al., 2007; Agosta et al., 2010). Reduced FA values in the left SLF have been found to positively correlate with performance on a variety of reading tasks in both ROI and whole brain analyses (Klingberg et al., 2000; Carter et al., 2009).

The SLF also was of interest due to the disparity in use of the terms ‘arcuate fasciculus’ and ‘superior longitudinal fasciculus’. Used synonymously in some literature, the two terms are elsewhere used distinctively. Others report the AF to be a portion of the SLF (Bernal & Altman, 2010). We were interested to see how the two tracts might be separated, and if this distinction could result in greater precision in our results.

Fornix. In order to substantiate potential correlations among the selected tracts of interest and behavioural measures, the fornix was selected as a control tract. This method adds some assurance that findings were not due to random correlations. To our knowledge, the fornix is not associated with reading.

METHODS

Subjects

The study included 12 Bilingual Chinese-English speakers (4 males and 8 females, mean age 24.2 years, SD 4.1 years). Participants were considered sequential bilinguals because they did not receive written English instruction earlier than 5 years of age. All participants were right-handed with normal or corrected to normal vision.

Behavioural data

Data were collected from participants individually in a normally lit room, where stimuli were presented. Each participant read three lists of words containing both exception (EXC) and regular words (REG). Measures of accuracy (ACC) and response time (RT) were recorded for each participant reading each list. The three lists varied in the number of exception and regular words included. The proportions were as follows: 1) 25% EXC and 75% REG (ventral and dorsal), 2) 50% EXC and 50% REG (ventral and dorsal), and 3) 75% EXC and 25% REG (ventral). Participants were given up to 1800ms to name the stimulus but were encouraged to work as quickly and accurately as possible. A microphone was used to code voice onset, and the experimenter recorded whether the response was correct or incorrect by pushing a mouse button (left = incorrect, right = correct). A fixation cross appeared on screen for 100ms preceding each stimulus.

Imaging

Participants had an MRI which included a DTI sequence with the following parameters: number of slices = 40, slice width = 3 mm (with no inter-slice gap), TR = 6900 ms, TE = 100 ms, 12 non-collinear directions of diffusion-sensitizing gradients, diffusion sensitivity b = 1000 s/mm^2, 5 b = 0 s/mm^2, 1 average, base resolution = 128×128, voxel size = 1.7×1.7×3.0 mm^3, and scan time = 4 minutes.

Fibre tracking protocol

Each tract of interest was reconstructed in both hemispheres in DTI Studio using a multiple regions of interest approach. Raw DTI images had not been spatially normalized, smoothed, or manipulated in order to avoid potential artifacts or loss of signal sensitivity. An FA threshold of 0.25 was used to initiate and continue tracking; the maximum angle threshold was 70 degrees. With reference to the protocols outlined in Wakana et al. (2004), Wakana et al. (2007), Dai (2013), Concha (2005), Narr (2009), and Mori et al. (2005), three types of ROI operations within DTI Studio were used for fibre tracking: “OR”, “AND”, and “NOT”. The “OR” function selects all the fibres that penetrate a particular ROI, the “AND” function selects only those fibres that penetrate both or all of the defined ROIs, and any undesired fibres can be removed using the “NOT” function. After the reconstruction of the tract, DTI Studio computed the three eigen values, and the mean FA value of each tract for each individual. The MD values were calculated as described earlier. Both FA and MD values were then correlated with the behavioural measures for reaction time and accuracy.

Tract Protocol

Uncinate Fasciculus. The UF (pictured in Figure 1) was isolated using the protocol outlined in Wakana et al. (2007). This protocol used two ROIs. The first is located in the most posterior coronal slice where green fibres connecting frontal and temporal lobes detach. After locating this slice, the researcher selected all of the fibres in the temporal lobe using the “OR” function. The second ROI was found in the same coronal slice. The researcher selected the bundle of fibres that project into the frontal lobe using the “AND” function. If a bundle of fibres was not clearly delineated from the first ROI, the researcher chose a more anterior coronal slice in which the fibres were separate. Finally, all fibres that were unrelated to the tract were removed using the “NOT” function. The same protocol was used for both hemispheres.

Inferior Fronto-Occipital Fasciculus. Using the protocol from Wakana et al. (2007), we were able to isolate the inferior fronto-occipital fasiculus (pictured in Figure 1). Two ROIs were used in this protocol. The first ROI was found in the coronal plane a few slices anterior to the splenium of the corpus collosum, in which the green fibres connecting the temporal and parietal lobes are visible. These same green fibres were selected using the "OR" function. The second ROI was found on a coronal slice at the anterior section of the fornix. Using the "AND" function the researcher drew the second ROI which was identified as a circular cluster of fibres that bunch together. Finally, the "NOT" function was used to remove any fibres that were not part of the tract. The same protocol was used for both hemispheres.

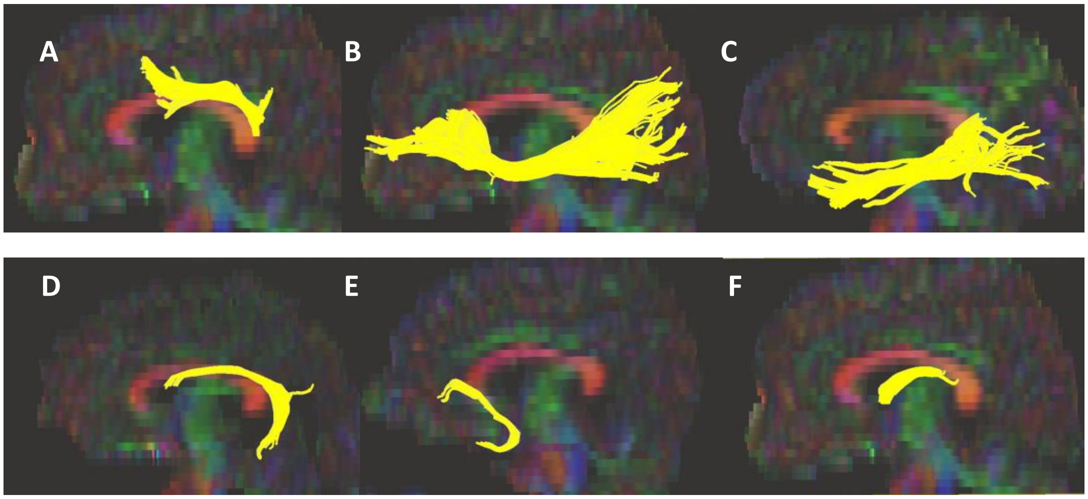
Inferior Longitudinal Fasciculus. The ILF (pictured in Figure 1) was isolated using the protocol outlined by Dai (2013) who also cited Narr (2009), Wakana et al. (2004), and Wakana et al. (2007). The first step was to locate the coronal slice showing the most posterior portion of the corpus callosum. There, the first ROI was drawn by selecting all the fibres in the left temporal and parietal lobes using the "OR" function. To draw the second ROI, the coronal slice in which the frontal lobe is disconnected from the temporal lobe was located. Using the "AND" operation, all the fibres in the temporal lobe were selected. Finally, the "NOT" operation was used to remove any fibres that clearly did not belong to the ILF (i.e. fibres that crossed into the opposite hemisphere). The same protocol was used for both hemispheres.

Arcuate Fasciculus. The AF (pictured in Figure 1) was isolated using the protocol outlined by Dai (2013), who followed Wakana et al. (2007). First, in the axial view, the most inferior slice in which the fornix is still visible was located. Then, in the coronal view, the researcher selected a slice that bisected the posterior limb of the internal capsule. Using the "OR" function, the first ROI was drawn to capture all the fibres in one parietal lobe (in the coronal view). Using the "AND" function, the second ROI was drawn on the axial slice to include the highlighted fibres just lateral to the sagittal stratum (SS). Finally, any fibres that crossed midline were removed using the "NOT" function. The same protocol was used for both hemispheres.

Superior Longitudinal Fasciculus. The SLF (pictured in Figure 1) was isolated following images presented in Mori et al. (2005). First, the most inferior slice in the axial view in which the fornix is still visible as one obvious unit was identified. Next, the coronal slice at the most posterior end of the fornix, in which the SLF is just visible, was selected. The first ROI was drawn using the "OR" function to select the bright green fibres of the SLF (as identified by Mori et al., 2005) in the coronal view. To draw the second ROI, the researcher identified the coronal slice that cut through the centre of the fornix, and selected the fibres identified as the SLF by Mori et al. (2005). Using the "NOT" function, any fibres that crossed midline or that extended inferiorly to the corpus callosum were removed. The same protocol was used for both hemispheres.

Fornix. The mid superior portion of the fornix (pictured in Figure 1) was selected as a control tract. Due to resolution restrictions, it was not possible to manually outline the entire fornix. Despite this limitation, the same mid top portion of the fornix was isolated for all participants. The protocol used to isolate the fornix was outlined by the Laboratory of Neuro Imaging at UCLA (2009) with a cross-reference to Concha et al. (2005). The first ROI was determined by identifying the axial slice in which the crus of the fornix was visible. In the colour map, this was the most inferior slice in which a central bright light blue spot is connected to surrounding green fibres. The second ROI was determined by identifying the coronal slice in which the cerebral peduncles were most visible. In the colour map, this slice was distinguished by the most intense bilateral colour change of the corticospinal fibres from blue to violet. The fibres inferior to the corpus callosum were selected as the second ROI.

Figure 1



A) Superior Longitudinal Fasciculus B) Inferior Fronto-Occipital Fasciculus C) Inferior Longitudinal Fasciculus D) Arcuate Fasciculus E) Uncinate Fasciculus F) Fornix

Reliabilities

Intra-rater reliability. To ensure intra-rater reliability, tracts were isolated twice in each hemisphere in a minimum of 20 percent of randomly selected participant MR images by, the same researcher. Comparing FA and MD values across tracts evidenced more than adequate Pearson product-moment correlation coefficients, as shown in Table 1 below.

Table 1: Intra-rater reliabilities

	UF left	UF right	IFOF left	IFOF right	ILF left	ILF right	Fornix left	AF left	AF right	SLF left	SLF right
FA	1.0	1.0	1.0	1.0	.998	.999	.997	.786	.998	.984	.957
MD	1.0	1.0	1.0	1.0	.987	.999	1.0	.853	1.0	.996	.952

Inter-rater reliability. Each tract was isolated again in each hemisphere in 10 percent of participant MRI scans by a second researcher, following the same protocol as the first researcher, to calculate inter-rater reliability. Comparing FA and MD values across researchers and tracts established a high overall Pearson product-moment correlation coefficient of r = .98.

RESULTS

All subjects completed the DTI sequence. No data were corrupted or needed to be discarded because of subject motion. All tracts of interest were isolated in both hemispheres of each subject. The fornix, was isolated only in the left hemisphere due to limitations of the DTI Studio software.

Behavioural Measures

Mean reaction times and mean accuracy rates are shown in Tables 2 and 3, respectively, below. Reaction times for REGs ranged from 424.81 to 887.2 ms, while the range for EXCs was 430.92 to 878.38 ms. Accuracy in naming REGs ranged from 0.73 to 1.0, whereas a broader range was observed in EXC word naming, with a range of 0.5 to 1.0.

Table 2: Mean Reaction Times

	Mean RT ms	SD
REG	584.32	112.98
EXC	595.46	115.36

Table 3: Mean Accuracy

	Mean ACC	SD
REG	.9589	.066
EXC	.8447	.106

Pearson Correlations

Control Tract. All correlations between behavioural measures and measures of FA or MD in the fornix had a *p*-value ≥ 0.09. This finding increases our confidence that correlations found of greater significance ($p \leq 0.05$) were not random correlations.

Ventral Pathway. The UF showed significant ($p \leq 0.05$) correlations with behavioural measures and both MD and FA. Significant negative correlations were found between FA values in the right UF (pictured in Figure 2) and participants' response times in the 25EXC75REG and

50EXC50REG conditions (see Table 4). In both of these conditions, we hypothesized the sub-lexical pathway to be involved. A significant positive relationship was also observed between MD and participants' response times in the 25EXC 75REG condition (see Table 5).

Table 4: Right Uncinate FA

	25 EXC 75 REG	50 EXC 50 REG	75 EXC 25 REG
Response Time	-.614 *p* = .034	-.583 *p* = .047	--
Accuracy	--	--	--

Table 5: Right Uncinate MD

	25 EXC 75 REG	50 EXC 50 REG	75 EXC 25 REG
Response Time	.590 *p* = .044	--	--
Accuracy	--	--	--

Dorsal Pathway. Several highly significant relationships were found in the dorsal tracts. Positive correlations were found between MD values in the right AF (pictured in Figure 2) and response times in all conditions (see Table 6). A negative relationship was also observed between MD in the right AF and accuracy in the 25EXC75REG condition.

Table 6: Right AF MD

	25 EXC 75 REG	50 EXC 50 REG	75 EXC 25 REG
Response Time	.722 *p* = .008	.641 *p* = .025	.662 *p* = .019
Accuracy	-.666 *p* = .018	--	--

The SLF was the only tract to demonstrate significant correlations with behavioural measures of reading in both hemispheres. Positive correlations were found between MD values in the right SLF (pictured in Figure 2) and response time in all reading conditions (see Table 7). An expected negative relationship was found between MD and accuracy in the 75% REG words condition.

Table 7: Right SLF MD

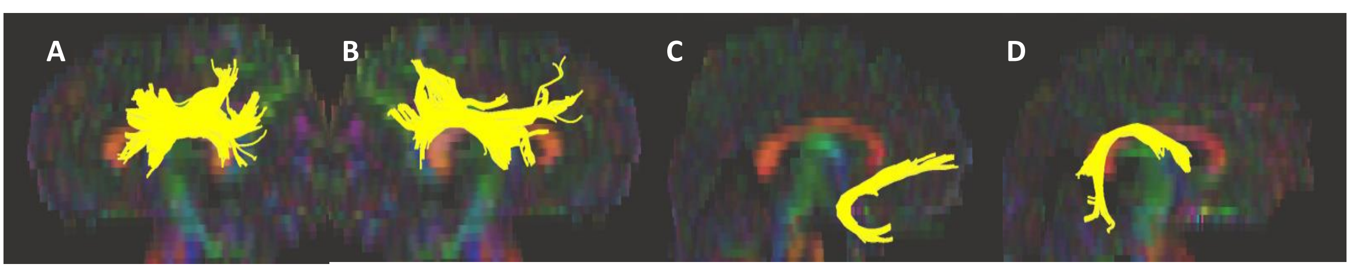
	25 EXC 75 REG	50 EXC 50 REG	75 EXC 25 REG
Response Time	.640	.585	.585
	p = .025	*p* =.046	*p* = .046
Accuracy	-.680	--	--
	p = .015		

Significant relationships were seen, as expected, between measures of integrity in the left SLF (pictured in Figure 2) and response times in all conditions (see Table 8). MD in the left SLF also correlated with accuracy in 75% REG and 75%EXC conditions.

Table 8: Left SLF MD

	25 EXC 75 REG	50 EXC 50 REG	75 EXC 25 REG
Response Time	.666	.617	.666
	p = .018	*p* = .033	*p* = .018
Accuracy	-.608	--	-.604
	p = .036		*p* = .038

Figure 2



A) Left Superior Longitudinal Fasciculus B) Right Superior Longitudinal Fasciculus
B) Right Uncinate Fasciculus D) Right Arcuate Fasciculus

DISCUSSION

Our investigation sought to examine the relationship between integrity of white matter tracts and reading ability in adult sequential bilinguals, as measured by response time and accuracy. We were particularly interested in tracts corresponding to ventral-lexical, streams and dorsal-sub-lexical streams. Three main findings emerged from the tracts isolated; 1) significant relationships exist between integrity of the right UF and participants' response times in the 25EXC 75REG condition; 2) positive correlations were found between MD values in the right AF and response times in all conditions; and 3) significant relationships exist between right AND left SLF integrity and response times in all conditions.

In the 25EXC75REG condition, we expected to find relationships between stronger reading ability (i.e. with fast reaction times and high accuracy scores) and higher integrity in both the lexical and sub-lexical systems. A strong lexical system would be required for a stronger performance, because the sub-lexical system would fail the reader 25% of the time. On the other hand, the sub-lexical system would work perfectly 75% of the time, and could be preferred, depending on the reader's familiarity with, and the frequency of occurrence of the words being named. Therefore, the integrity of both systems were expected to be relevant in the predominantly REG words condition. We found in this condition that the UF, a ventral tract, was significantly related to reading ability. It is possible that Chinese bilinguals prefer using the whole-word (i.e. ventral) approach even in this condition where a dorsal approach would be more efficient. It has been suggested that bilingual participants use their native language systems in second language reading and the Chinese writing system uses characters to represent the whole word (Tan et al. 2003).

In the split condition, we expected to find a relationship between reading ability and the integrity of the lexical system, more so than that of the sub-lexical system. Success in the split condition would require a strong lexical system because the sub-lexical (dorsal) system would produce an incorrect response 50% of the time (thus necessitating the lexical system). On the other hand, the lexical system could potentially process the REGs without calling on the sub-lexical system, so a strong sub-lexical system would not be required for speed and accuracy in this condition. In this study we did indeed find that the lexical system played a role (UF); however, in bilinguals the dorsal stream (AF, SLF) also played a very significant role in processing. It is possible that the dorsal route plays a role in the split condition considering that Bialystok, Luk, & Kwan (2005) demonstrated that only when languages are using the same writing system are the reading skills transferred. Since Chinese and English have different writing systems one can expect different strategies than expected.

In the predominantly exception words condition (75EXC25REG), we expected a relationship between reading ability and integrity of the lexical system. The lexical system would be required 75% of the time in order to correctly name the stimuli in this condition (for all EXCs). Since REG words could, potentially, be named by the lexical system, the reader could rely on it completely in this condition and still quickly and accurately name stimuli (i.e. integrity of the sub-lexical system could be irrelevant). Therefore, we would not expect a relationship between integrity of the sub-lexical system and speed and accuracy in this condition. However, that is exactly what we found: a significant relationship between the SLF and AF and reading skill in the 75% EXC condition, and no apparent relationship with the ventral tracts. The reason might have to do with exception words not being as easily recognized by bilinguals or that they have not been as exposed to exception words. Bilinguals might therefore try using their dorsal route if English is their second language and they were taught to sound out words when learning to read in English.

An interesting finding of the current work was an unexpected relationship between behaviour and some of the right hemisphere white matter pathways. To help explain this finding we look to some previous studies. Osipowicz et al. (2011) found that lexical decoding appeared to be associated with right middle frontal activation, while Levy et al. (2008) found that right hemispheric lateralization in processing of novel items was stronger. De Diego Balaguer et al. (2006) also supports this notion with the finding that exception production activates the bilateral inferior frontal area and dorsolateral pre-frontal cortex. Another study by Luk et al. (2011) found increased FA in the right UF in bilinguals compared to monolinguals. This might suggest the increased integrity of right hemisphere white matter pathways in bilinguals. A study by Senaha et al. (2005) looked at patterns of cerebral activation during lexical and phonological reading, and found that reading involvement was greater in the right hemisphere when reading words more so than non-words. As well, the activation was greater in the areas of the superior, middle, and inferior frontal gyri. Given the connection of the UF to the orbitofrontal cortex (Catani et al., 2002) it is possible that the right UF could play a role in what Senaha et al. (2005) described as stated earlier. These studies, along with our findings, show that it is possible that the right UF is more developed in bilinguals and could play a role in words that have atypical spelling-to-sound correspondences.

Curiously, like the UF, the AF showed a significant relationship with reading ability only in the right hemisphere, while the SLF was the only tract to show bilateral significance. Because non-words and pseudo-homophones were not included in our study, we did not have a condition that might implicate either of these tracts strictly for sub-lexical processing. However, the integrity of both of these tracts, even in the right hemisphere, appears to have something to do with reading ability in general. In the case of our Chinese-English sequential bilingual population the significance of the right hemisphere pathways can be explained by previous findings. It has been suggested that reading acquisition is initially a right hemisphere process (Orton, 1937), and that involvement of the right hemisphere in reading and language tasks decreases as a function of skill (Raboyeau et al., 2004). Because the subjects involved in our study had learned to read in at least two distinct orthographic systems, they would have utilized the aforementioned neural connections (for learning) considerably more than a monolingual would have. Additionally, and perhaps most importantly, the reading of Chinese characters has been described as a visuo-spatial task (Booth et al., 2005), and visuo-spatial tasks have been shown to predominantly activate the right parietal regions (Smith et al., 1996; Zurowski et al., 2002).

Finding the SLF to be significant in the left hemisphere, and not the AF relates to our earlier question regarding the separation of the two tracts. Efforts to examine the two tracts distinctly proved worthwhile in that the left SLF without the AF portion showed significant correlations with reading ability in the bilingual sample studied. Meanwhile the integrity of the AF alone was not significant in the left hemisphere in the population studied.

Future research could attempt to examine the following questions: how do white matter tracts in the areas outlined differ between bilingual and monolingual participants? Does the integrity of the white matter in dorsal pathways (e.g. superior longitudinal fasciculus) have a positive relationship with stimuli known to activate dorsal regions (e.g. non-words, pseudohomophones)? Does the written system of the second language influence the integrity of certain white matter pathways? Another study by Mohades et al. (2011) examined structural differences in white matter tracts between bilingual and monolingual children and further analyzed the differences between sequential and simultaneous bilinguals. In this study the simultaneous bilingual had higher FA in the left inferior occipital frontal fasciculus. Thus it would be interesting to examine whether the time of second acquisition is different into adulthood.

CONCLUSION

To our knowledge, this is the first study using DTI to investigate the integrity of neural pathways in the both hemispheres associated with reading in adult bilinguals. In sum, we provide evidence to suggest that the integrity of left and right SLF, right AF, and right UF correlate with English reading ability (measured by speed and accuracy) in Chinese-English sequential bilinguals.

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