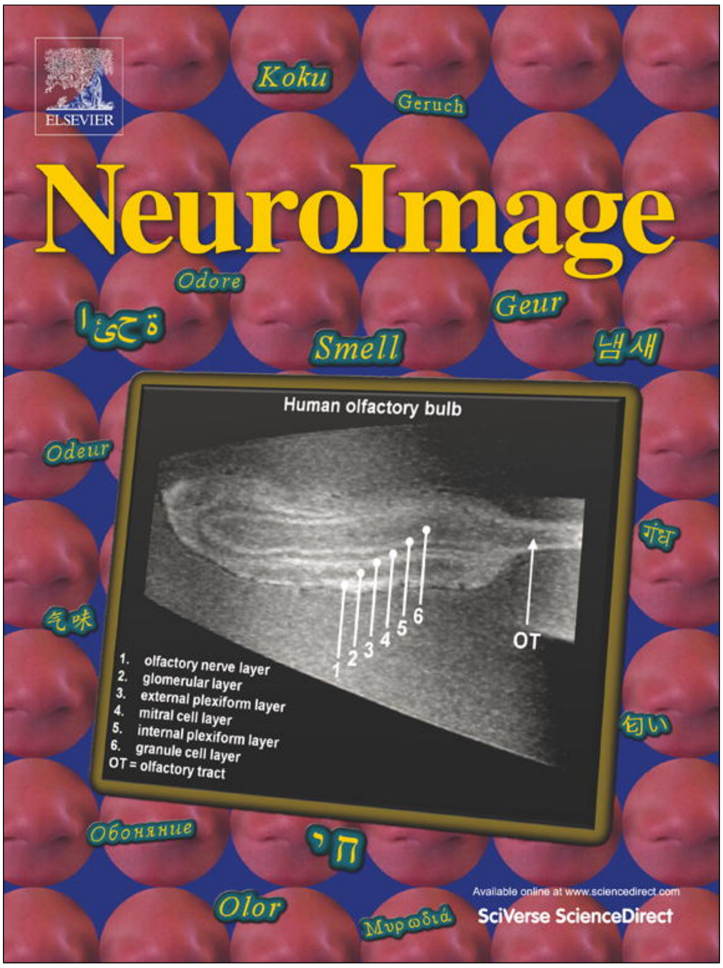
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The contribution of the left mid-fusiform cortical thickness to Chinese and English reading in a large Chinese sample

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A B S T R A C T

Previous functional neuroimaging studies have shown that the left mid-fusiform cortex plays a critical role in reading. However, there is very limited research relating this region's anatomical structure to reading performance either in native or second language. Using structural MRI and three reading tasks (Chinese characters, English words, and alphabetic pseudowords) and a non-reading task (visual–auditory learning), this study investigated the contributions of the left mid-fusiform cortical thickness to reading in a large sample of 226 Chinese subjects. Results showed that the cortical thickness in the left mid-fusiform gyrus was positively correlated with performance on all three reading tasks but not with the performance on the non-reading task. Our findings provide structural evidence for the left mid-fusiform cortex as the "gateway" region for reading Chinese and English. The absence of the association between the left mid-fusiform cortical thickness and non-reading performance implied the specific role of this area in reading skills, not in general language skills.

Introduction

Previous studies have suggested that the left mid-fusiform cortex plays a critical role in reading (Cohen et al., 2000, 2002; Koyama et al., 2011; Mei et al., 2010; Price and Devlin, 2004; Xue et al., 2006a). Functional imaging studies found consistent involvement of this area in word reading across different languages (both first and second languages, both alphabetic and logographic writings) (Bolger et al., 2005; Tan et al., 2005; Xue et al., 2006a). Furthermore, better reading skills were associated with stronger activity in the left mid-fusiform cortex in studies of Swiss-German adolescents and adults (Brem et al., 2006) and 6- to 22-year-old native English speakers (Turkeltaub et al., 2003; also see a review by Schlaggar and McCandliss, 2007). Studies of Chinese adults also found that activation of the mid-fusiform cortex predicted both short-term and long-term performance in learning to read an artificial language (Chen et al., 2007; Dong et al., 2008; Xue et al., 2006b, 2010). Recent studies of American adults further demonstrated that resting-state functional connectivities between this area and other reading-related regions (Koyama et al., 2011) and the attention network (Vogel et al., 2012) were associated with English reading competence.

Further support for the role of the left mid-fusiform cortex in reading came from research on individuals with dyslexia. Children and adults with dyslexia (i.e., individuals with normal IQ but whose reading performance was lower than two standard deviations below their peers' average score) have been found to show abnormal function in this area as compared to non-impaired controls (McCrory et al., 2005; van der Mark et al., 2009). Moreover, structural imaging studies have revealed decreased gray matter volume in the left mid-fusiform cortex among German-speaking adolescents with dyslexia (Kronbichler et al., 2008) and French-speaking adults with dyslexia (Pernet et al., 2009). Similarly, Silani et al. (2005) found reduced gray matter density in Italian, French, and English adults with dyslexia in this region as compared to non-impaired readers.

It is worth noting that because of the importance of the left mid-fusiform cortex in reading visual words, some researchers have even labeled this region as the "visual word form area" (VWFA) (Cohen et al., 2000, 2002). This label has been controversial because it implies that this region's function is exclusively for visual word form processing (Mei et al., 2010; Price and Devlin, 2003, 2004; Xue et al., 2006a). Despite the controversy about its exclusivity, researchers have a general consensus about this region's crucial role in reading. In fact, some researchers (Bolger et al., 2005; Perfetti and Bolger, 2004) have considered this region as the "gateway" region for reading that subserves visual analysis of words or orthographic form processing. Through this "gateway", critical invariant information is extracted from visual forms

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and interacts with linguistic representations (Schlaggar and McCandliss, 2007). Their assertion was based on the consistent activation of this region in word and word-like reading across different languages as mentioned earlier and also on the larger early electrophysiological response (150 ms–200 ms) in this region to visual words and word-like materials than to other stimuli such as common objects (Bentin et al., 1999; Rossion et al., 2003; Xue et al., 2008; Zhang et al., 2011).

Despite the importance of this region in reading, few studies have examined this region's anatomical variations and reading abilities in non-impaired readers. Our literature search produced a limited number of studies linking brain structure to language abilities among non-impaired populations. Among them, only two examined reading (Blackmon et al., 2010; Welcome et al., 2011), with the others investigating speech production (Golestani and Pallier, 2007; Grogan et al., 2009, 2012; Porter et al., 2011), vocabulary knowledge (Lee et al., 2007; Richardson et al., 2010), novel sound perception and production (Golestani et al., 2002, 2007), and overall second language proficiency (Mechelli et al., 2004).

Blackmon et al. (2010) studied 60 American subjects (24 to 50 years of age) and used one reading task (i.e., reading irregular English words). They found that cortical thickness in the left mid-fusiform cortex was negatively correlated with the ability to read irregular English words. In another study of 55 college students who were English native speakers, Welcome et al. (2011) compared the gray matter thickness of eight ROIs in each hemisphere between poor and good readers on two tasks (i.e., alphabetic pseudoword reading and text comprehension). However, the left mid-fusiform cortex was not included as an ROI. They found that altered asymmetry in the temporo-parietal region was associated with poorer pseudoword reading and reduced cortical thickness in the right inferior frontal region was associated with poorer text comprehension. Though informative, these two studies are limited in the specific tasks used (i.e., irregular words in Blackmon et al. (2010) and pseudowords in Welcome et al. (2011)) and sample size. Furthermore, the age range of the subjects in Blackmon et al.'s study was large, which might have introduced brain development as a confounding factor.

To further understand the associations between the structure of the left mid-fusiform cortex and reading abilities, the current study used a large sample of 226 Chinese subjects and included three reading tasks (Chinese characters, English words, and alphabetic pseudowords) and one non-reading task (visual–auditory learning). Because the left mid-fusiform cortex has shown consistent activation across different languages (Bolger et al., 2005; Nakamura et al., 2005; Tan et al., 2005), we expected that the structure of this region would be linked to reading performance of both native Chinese characters and second language English words. The hypothesis about alphabetic pseudoword reading was more tentative. Some older evidence suggested that pseudoword reading engaged more of the dorsal route areas such as the dorsal temporo-parietal cortex (phonological decoding) than the ventral temporo-occipital cortex (whole word retrieval) (Fiebach et al., 2002; Pugh et al., 2000) but others did observe the ventral pathway for pseudoword reading (Heim et al., 2005; Mechelli et al., 2003). Most studies have observed equal (even stronger) activity in the left mid-fusiform cortex in pseudoword reading compared to real word reading (Bolger et al., 2005; Cohen et al., 2002, 2008; Liu et al., 2008; Vigneau et al., 2005). Therefore, we expected that this region would also be associated with performance on pseudoword reading.

More specifically, we expected that the correlations would be positive between cortical thickness of this region and all reading tasks. This was based on the two lines of previous research mentioned above. First, there was consistent evidence that readers with dyslexia showed reduced volume and/or density in the left mid-fusiform area as compared to non-impaired controls. Second, most research on the associations between brain structures and language abilities found positive associations. For example, Golestani and Pallier (2007) showed that higher white matter volumes in bilateral inferior parietal cortices, left Heschl's gyrus, left insula cortex and left prefrontal cortex were associated with better speech (novel sounds) production (Golestani and Pallier, 2007). Similarly, gray matter density in bilateral posterior supramarginal gyri was associated with overall second language proficiency (Mechelli et al., 2004) and vocabulary knowledge (Lee et al., 2007; Richardson et al., 2010). Also, speech production was positively linked to the gray matter density of other language-related regions, such as the left inferior frontal cortex (Grogan et al., 2012), bilateral inferior temporal cortices, bilateral pre-supplementary motor areas and bilateral head of the caudates (Grogan et al., 2009). Blackmon et al.'s (2010) finding of a negative association between cortical thickness and reading irregular words was an exception. Their results are hard to explain because they contradict the findings from research on individuals with dyslexia and from other language tasks and brain regions. A possible reason for their finding is the large age range of their subjects, which may have introduced brain development as a confounding factor.

To ascertain whether the structure of the left mid-fusiform cortex is linked to a non-reading language task, we included a visual–auditory learning task. If the left mid-fusiform cortex plays a specific role in reading, its structure would not be associated with this non-reading language task.

Materials and method

Subjects

Two hundred and twenty six Chinese students (age range: 20–24 years, mean age = 21.7, SD = 0.88, 134 female and 92 male) from Beijing Normal University participated in our experiment. All were native Chinese speakers, learning English as their second language (since elementary school) and passed the college entrance examination of Chinese and English. They had normal or corrected-to-normal vision, with no previous history of neurological or psychiatric diseases and were strongly right-handed as judged by Snyder and Harris's handedness inventory (Snyder and Harris, 1993). Informed written consent was obtained from the subjects before the experiment. This study was approved by the IRB of the National Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

Behavioral assessment

English word and alphabetic pseudoword reading were assessed using the Test of Word Reading Efficiency (TOWRE), a nationally normed measure of word reading accuracy and fluency in the U.S. for individuals from 6 to 24 years of age (Torgesen et al., 1999). TOWRE contains two subtests, Sight Word Efficiency (SWE) and Pseudoword Decoding Efficiency (PDE). SWE was indexed by the number of printed words that were accurately read within 45 s, and PDE by the number of pronounceable printed non-words (i.e., pseudowords) that were accurately decoded/read within 45 s. Test items were arranged in order of difficulty from easy items to more difficult items. Each subtest has two equivalent forms (A and B), both of which include 104 items. Both forms were administered in the current study and their scores were averaged.

Chinese character reading was measured by the Chinese Character Reading Efficiency Test (CCRET). This test was developed for the current study in the format of SWE. There were 104 items in the CCRET selected from Chinese character psycholinguistic norms (Liu et al., 2007) with word frequency ranging from 4 to 5636 (mean = 196), number of strokes ranging from 2 to 14 (mean = 7.3), and number of units ranging from 1 to 5 (mean = 2.4). Reading efficiency was indexed by the number of printed Chinese characters that were accurately read in 45 s. Test items were arranged in order of difficulty from easy items to more difficult items. There was no pseudoword test in Chinese because Chinese is a logographic language in which there are only nonwords (that cannot be pronounced) but no pronounceable pseudowords.

The non-reading language task was the Visual–Auditory Learning test, a subtest of Woodcock Reading Mastery Test—Revised (WRMT-R, Woodcock, 1987). This subtest assesses the ability to form associations between visual stimuli (non-language symbols) and oral responses. Subjects learned 26 unfamiliar symbols by associating them with familiar words, and then translated sentences using those new symbols. Test items were arranged in order of difficulty from short symbol strings to long sentences. Subjects must respond within 5 s to each symbol. The experimenter circled each error the subject made on the test record. The final score was the number of correct responses out of a total of 134 items.

MRI data acquisition

MRI scans were performed on a 3.0T Siemens Magnetom Trio scanner equipped with a standard head coil. Structural MRI data were acquired with the T1-weighted, three-dimensional, gradient-echo (MPRAGE) pulse sequence. Subjects were scanned at Beijing Normal University's Brain Imaging Center with the following imaging parameters: TE = 3.75 ms, TR = 2530 ms, flip angle = 7°; FOV = 256 mm × 256 mm, voxel size = 1 × 1 × 1.33 mm^3, and number of partitions = 128.

MRI data analysis

Surface reconstruction and thickness measures

MRI data were analyzed with FreeSurfer software package (http://surfer.nmr.mgh.harvard.edu/). A model of each subject's cortical surface was constructed through an automated procedure, which involves segmentation of the white matter, tessellation of the gray/white matter boundary, inflation of the folded surface tessellation patterns, and automatic correction of topological defects (Dale et al., 1999; Fischl and Dale, 2000; Fischl et al., 1999). From the reconstructed surface, measures of cortical thickness were calculated as the shortest distance from the gray/white boundary to the pial surface at each vertex on the tessellated surface (Fischl and Dale, 2000). Thickness measurements were mapped onto the "inflated" surface of each subject's reconstructed brain to be visualized without interference from cortical folding. The maps were created using spatial intensity gradients across tissue classes and continuity information from the entire 3D MRI volume. Quality control was assured by visual inspection of the entire cortex in each subject, and any inaccuracies in Talairach-transformation, skull stripping and segmentation were manually corrected and then re-inspected. Cortical thickness maps were then smoothed using a Gaussian kernel (10 mm FWHM).

Region-of-interest (ROI) analysis

The current study mainly focused on the contribution of the left mid-fusiform cortex to reading and non-reading tasks. We used two methods to determine the relationship between cortical thickness in this region and performances on these tasks. First, we did a vertex-by-vertex calculation of thickness in the left fusiform gyrus (using the label of FreeSurfer, Fig. 1) in relation to behavioral performances. That is, after surface reconstruction, a general linear model was used to estimate the effects of reading performance on thickness at each vertex along the cortical surface of the left fusiform gyrus. Because previous studies showed significant gender differences in brain anatomy (Im et al., 2006; Luders et al., 2006; Smith et al., 2007) and hence it is common to include gender as a covariate in structural brain research (Fleming et al., 2010; Kanai et al., 2010), we also included gender as a covariate in the current study. Significance maps ($p<.05$) were then corrected for multiple comparisons with cluster-based Monte Carlo simulations with 10,000 permutations. This simulation is a way to measure the distribution of the maximum cluster size under the null hypothesis, using the *FreeSurfer* program mri_glmfit-sim (https://surfer.nmr.mgh.harvard.edu/fswiki/FsTutorial/GroupAnalysis). It is a widely used cluster-wise correction method employed not only by the *FreeSurfer* to analyze MRI data (Blackmon et al., 2010; Porter et al., 2011) but also by other tools for fMRI data analysis (e.g., AFNI's AlphaSim program (http://afni.nimh.nih.gov/afni)). Finally, corrected significance values ($p<.05$) of thickness in the fusiform gyrus's correlations with behavioral scores were mapped onto the surface of the average reconstructed brain for visual display.

To focus on the left mid-fusiform cortex reported by previous studies, our second method used TkSurfer, an interface in the FreeSurfer toolset (http://surfer.nmr.mgh.harvard.edu/fswiki/tksurfer_labeledit) to create the ROI (6-mm radius) on the surface template, a circle centered at x = −42, y = −58, z = −21 (MNI coordinates, which are used for the presentation of results in this paper). This center was selected based on the localization of the so-called VWFA defined by Cohen and his colleagues and consistently reported by other studies (Bolger et al., 2005; Chen et al., 2007; Mei et al., 2010; Xue et al., 2006a). For this study, we transformed the previous Talairach coordinates (x = −42,

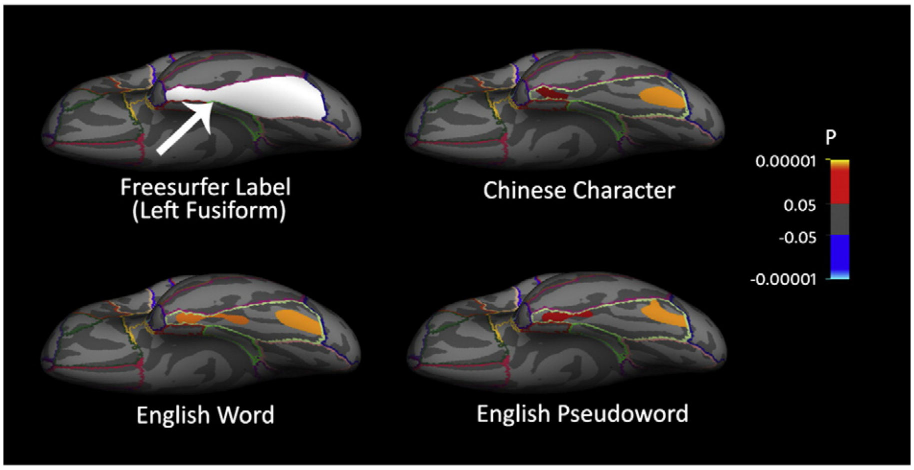

Fig. 1. The left fusiform gyrus as labeled in FreeSurfer and clusters that showed significant associations between reading skills and cortical thickness in the left fusiform gyrus (with gender as a covariate). Results are displayed on the group-averaged inflated surface. Statistical P maps were thresholded at $p<0.05$, cluster-corrected in the left fusiform gyrus. No cluster was significant for the visual–auditory learning task.

y = −57, z = −15) (McCandliss et al., 2003, p. 294, Fig. 1 in the original article) into MNI coordinates using a MatLab script from http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach. The ROI was then mapped back to the reconstructed brain of each subject and mean cortical thickness was extracted for every subject to conduct regression analysis with the behavioral scores. Gender was included as a covariate. Although this study aimed to focus on the contributions of the left mid-fusiform cortex to reading, readers might be interested in a whole-brain analysis that explored other regions relevant to reading performances as well as the visual–auditory learning performance. Please see Online Supplementary Materials for details of the method, results, and discussion of the whole brain analysis.

Results

As shown in Table 1, mean scores (and standard deviations) for Chinese character reading, English word reading, alphabetic pseudoword reading, and visual–auditory learning were 87 (11.1), 73 (8.4), 43 (7.7), and 123 (10.1), respectively. The correlations among the three reading tasks' scores were all significant ($p<.001$): $r=.559$ between Chinese character reading and English word reading, $r=.359$ between Chinese character reading and alphabetic pseudoword reading and $r=.766$ between English word reading and pseudoword reading. Visual–auditory learning was significantly correlated with English word reading ($r=.193$, $p<.005$) and marginally correlated with pseudoword reading ($r=.113$, $p=0.066$), but not with Chinese character reading ($r=.069$, $p=0.3$).

Table 2 shows the vertex-by-vertex analysis focusing on the left fusiform cortex (also see Fig. 1). Two clusters in the left fusiform gyrus were significantly associated with performance of reading Chinese characters (x = −37.8, y = −62.7, z = −16.8, corrected $p<.0001$; x = −33.6, y = −10.5, z = −32.5, corrected $p<.05$), English words (x = −39.2, y = −66.1, z = −17.3, corrected $p<.0001$, x = −35.2, y = −8.6, z = −36.7, corrected $p<.001$) and English pseudowords (x = −42.8, y = −60.2, z = −19.9, corrected $p<.0001$; x = −34.4, y = −8.4, z = −35.4, corrected $p<.01$). Thicker cortex was associated with better reading abilities. No cluster showed negative associations with reading abilities after correcting for multiple comparisons. For visual–auditory learning, no cluster showed positive or negative associations after correcting for multiple comparisons.

These results were further confirmed by ROI analysis (see Fig. 2). The mean thickness of the structural ROI was significantly and positively correlated with reading performance of Chinese characters ($p<.05$), English words ($p<.005$) and pseudowords ($p<.01$), but not with visual–auditory learning ($p=0.4$). We then used the Fisher r-to-z transformation and assessed the significance of the differences between the correlation coefficients of cortical thickness with reading and non-reading tasks. There was marginally significant difference between the correlation coefficient for visual–auditory learning and that for reading English words (z = 1.6). The differences did not reach significance between the correlation coefficients for visual–auditory learning and Chinese character reading (z = 1.0) or between those for visual–auditory learning and pseudoword reading (z = 1.2).

Table 1
Characteristics of subjects.

Characteristics	
Age	21.7 (0.9)
Gender	134 female 92 male
Chinese character reading score	87 (11.1)
English word reading score	73 (8.4)
English pseudoword reading score	43 (7.7)
Visual–auditory learning score	123 (10.1)

Note: Standard deviations are shown in parentheses.

Table 2
Clusters in the left fusiform related to multiple language skills ($p<0.05$, corrected in the left fusiform).

	Related clusters (MNI)	Size (mm)	Cluster corrected p
Chinese reading	x = −37.8, y = −62.7, z = −16.8	459.36	$p<.0001$
	x = −33.6, y = −10.5, z = −32.5	214.40	$p<.05$
English reading	x = −39.2, y = −66.1, z = −17.3	455.43	$p<.0001$
	x = −35.2, y = −8.6, z = −36.7	358.28	$p<.001$
Pseudoword reading	x = −42.8, y = −60.2, z = −19.9	394.03	$p<.0001$
	x = −34.4, y = −8.4, z = −35.4	258.56	$p<.01$
Visual–auditory learning	ns		

Discussion

The current study investigated the relationship between cortical thickness in the left mid-fusiform cortex and multiple language skills in Chinese readers. We found that the left mid-fusiform cortical thickness contributed to the performance on three reading tasks (native Chinese characters, second language English words, and alphabetic pseudowords), but it was not associated with a non-reading language task (i.e., visual–auditory learning). In the following sections, we discuss the role of the left mid-fusiform cortex in reading and non-reading tasks.

Our results that thicker cortex in the left mid-fusiform cortex was associated with better native and second language reading in Chinese subjects supported our hypothesis derived from previous research. First, previous functional imaging studies have implicated this area for visual word form processing across different languages (logographic and alphabetic languages, first and second languages, real words and word-like materials) (Bolger et al., 2005; Jobard et al., 2003; Nakamura et al., 2005; Nelson et al., 2009; Tan et al., 2005; Xue et al., 2006a). This area's functional activation was associated with reading skills (Brem et al., 2006; Koyama et al., 2010, 2011; Schlaggar and McCandliss, 2007; Turkeltaub et al., 2003). To our knowledge, this is the first study to reveal the structural contribution of the left mid-fusiform cortex to multiple reading tasks in a large sample.

Second, our results are also consistent with the research literature on individuals with dyslexia that showed reduced density and volume in this area in readers with dyslexia compared to non-impaired controls (Kronbichler et al., 2008; Pernet et al., 2009; Silani et al., 2005; Vinckenbosch et al., 2005). Our study of a general college sample suggests that the left mid-fusiform cortex could be considered as structural marker for skilled and poor readers, not only in native language reading but also in second language reading. This finding further supports the idea that the left mid-fusiform is the "gateway" of reading and plays an important role in both first and second language reading. Indeed, previous research has suggested common mechanisms underlying reading difficulties in both native and second languages. For example, Ho and Fong (2005) showed that Chinese children with dyslexia based on their difficulty in reading Chinese were found to perform poorly as well in nearly all measures of English reading. Similarly, Iranian students with dyslexia were also found to encounter many difficulties in learning English and Arabic as foreign languages and to show poor performance in spelling, reading and phonological processing as compared to normal students (Ghazaleh, 2011). Finally, a recent study found that Chinese children with English and Chinese reading impairments showed reduced activation in the left occipitotemporal region during orthographic processing (You et al., 2011). In sum, our finding that cortical thickness of the left mid-fusiform gyrus was positively linked to reading performance in both native and second languages can be integrated into the literature on neural bases of dyslexia.

It should be pointed out that our results are inconsistent with the one recent structural study of normal subjects that showed a negative association between cortical thickness in this area and irregular word

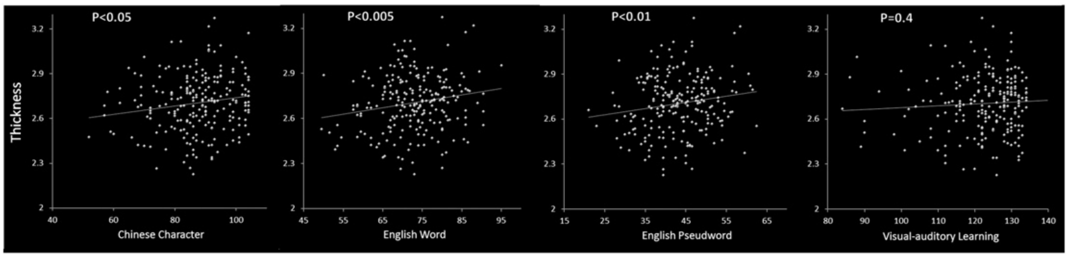

Fig. 2. The relationship between language skills (Chinese character, English word, and pseudoword reading, and visual–auditory learning) and mean cortical thickness of the created ROI, a 6-mm radius circle centered at x = −42, y = −58, z = −21 (MNI coordinates).

reading (Blackmon et al., 2010). As mentioned in the Introduction, Blackmon et al.'s findings appeared to contradict both the literature from research on individuals with dyslexia and on other brain regions and language skills. Their particular task (irregular word reading) and the wide age range of their subjects (from 24 to 50 years) might have contributed to their particular findings. More research is needed with a wider array of tasks and different age groups to clarify the inconsistencies in the literature.

The biological mechanism involved in cortical thickness' connection to behavior is a complicated issue and is still not well understood. Cortical thickness measured in our study is an index of the structure of the brain's outer surface. Within this thin sheet, strong local connections (0–3 mm) between neurons are formed, which form local processing units. More remote connections such as those between different gyri or the two hemispheres are achieved via white matter tracts (Jancke et al., 2009). Because the brain cortex contains cell bodies, neuronal synapses, unmyelinated axons, dendrites, etc., variations in any of these in a brain region could influence its structural and functional properties. Increased cortical thickness might be due to a greater arborization per neuron, increased glial volume or regional vasculature (Blackmon et al., 2010; Jancke et al., 2009). In addition to genetic factors (Yoon et al., 2010), cortical thickness is also affected by environmental factors such as experience, practice or learning (Gaser and Schlaug, 2003; Kelly and Garavan, 2005). For example, in terms of language learning's effect on brain structure, a previous study showed that second language experience increased gray matter density in the left inferior parietal area (Mechelli et al., 2004). Future research should investigate the sources of variations in cortical thickness (genetic or environmental factors, arborization or glial growth) and clarify their associations with behavioral performance such as reading.

Third, by including a non-reading language task (i.e., visual–auditory learning), our results showed that the left mid-fusiform cortical thickness did not contribute to visual–auditory learning. It is consistent with previous studies that explored the structural basis of non-reading language skills and found no significant effects of the mid-fusiform region (Golestani and Pallier, 2007; Golestani et al., 2002, 2007; Grogan et al., 2009, 2012; Lee et al., 2007; Mechelli et al., 2004; Porter et al., 2011; Richardson et al., 2010). Instead of the left mid-fusiform cortical thickness, the thickness of the left inferior temporal gyrus was found in this study to be associated with performance on visual–auditory learning (see Supplementary Online Materials). This area has been implicated in the representation of conceptual knowledge (Sharp et al., 2004), lexical access and semantic retrieval (Heim et al., 2009; Hickok and Poeppel, 2007; Price, 2000), and semantic processing (Bolger et al., 2005; Vigneau et al., 2006). In fact, one recent structural study revealed that the gray matter density of the inferior temporal cortex was associated with semantic fluency in both first and second languages (Grogan et al., 2009). The left inferior temporal cortex contributed to visual–auditory learning in our study perhaps because this task required the subjects to associate visual symbols with verbal labels with semantics and concept representation.

In addition to the mid-fusiform cortex, we also observed the effect in the anterior fusiform gyrus on reading. At the functional level, some previous studies have revealed a dissociation in the subregions of the fusiform cortex, with activation in the anterior fusiform region becoming more selective for higher-level language processing (Mechelli et al., 2005; Seghier and Price, 2011; Vinckier et al., 2007). That is, pseudoword reading was associated with the posterior part of the fusiform, whereas word reading with the anterior part. Our study did not observe such a differentiation. There are two possible explanations. First, it is possible that this finding may be specific to Chinese readers to whom English words and alphabetic pseudowords are not native. Therefore, a greater region of the fusiform gyrus is involved in learning to read foreign words due to a compensatory process. Second, the distinction between real word and pseudoword reading was subtle in the functional data and such a subtle difference was not revealed by the perhaps less sensitive structural analysis with the present technology. Future structural studies should further examine this issue by including more variations of the reading tasks and more subjects with different native languages.

In summary, with a large Chinese sample and three reading tasks and a non-reading task, the current study found that the left mid-fusiform cortical thickness made a positive and significant contribution to reading in native and second languages. These findings have important implications to our understanding of anatomical basis of reading in non-impaired subjects. The absence of the effect in visual–auditory learning implies structural specificity of the mid-fusiform cortex to reading. There are three main limitations in current study that should be addressed in future research. First, as a correlational study, the current study could not clarify the causal relationship between reading performance and the left mid-fusiform cortical thickness. The association we found may have been due to the brain's effects on learning to read or reading's effects on brain structure. Future research should address the issue of neural plasticity vs. neural constraints. Future research should include child subjects to test whether early anatomical differences predicted later reading ability or reading behavior predicted anatomical changes or both. Long-term training paradigm can also be used for this purpose. Second, the current study only used one non-reading task. Additional non-reading tasks should be used to investigate the specificity of the left mid-fusiform cortical thickness for reading. Third, the current study used a Chinese reading test that was developed based on its English equivalent. This test needs refinements as well as normative data.

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Appendix A. Supplementary data

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