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Long-term experience with Chinese language shapes the fusiform asymmetry of English reading

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ABSTRACT

Previous studies have suggested differential engagement of the bilateral fusiform gyrus in the processing of Chinese and English. The present study tested the possibility that long-term experience with Chinese language affects the fusiform laterality of English reading by comparing three samples: Chinese speakers, English speakers with Chinese experience, and English speakers without Chinese experience. We found that, when reading words in their respective native language, Chinese and English speakers without Chinese experience differed in functional laterality of the posterior fusiform region (right laterality for Chinese speakers, but left laterality for English speakers). More importantly, compared with English speakers without Chinese experience, English speakers with Chinese experience showed more recruitment of the right posterior fusiform cortex for English words and pseudowords, which is similar to how Chinese speakers processed Chinese. These results suggest that long-term experience with Chinese shapes the fusiform laterality of English reading and have important implications for our understanding of the cross-language influences in terms of neural organization and of the functions of different fusiform subregions in reading.

Introduction

Previous cross-linguistic neuroimaging research has shown significant interactions between the native language and the second language in the brain. On the one hand, the native language can shape the cognitive and neural mechanisms of second language processing (Nakada et al., 2001; Nelson et al., 2009; Tan et al., 2003; Wang et al., 2003); and on the other hand, second language learning affects the neural mechanisms of native language (Mei et al., 2014; Nosarti et al., 2010; Zou et al., 2012). To account for the cross-language influences, Perfetti and colleagues have proposed the assimilation–accommodation hypothesis (Perfetti and Liu, 2005; Perfetti et al., 2007). The assimilation process assumes that the human brain will read a second language as if it is the native language and use the neural network for the native language to support the second language (Cao et al., 2013a; Nelson et al., 2009). The accommodation process assumes that the brain's reading network must adapt to the features of a new writing system in order to accommodate those features that require different reading procedures (Cao et al., 2013b; Liu et al., 2007; Nelson et al., 2009; Zhao et al., 2012).

Chinese–English bilinguals provide a unique opportunity to investigate cross-language influences, because English and Chinese languages differ in several important aspects such as visual appearance and orthographic transparency (Bolger et al., 2005; Chen et al., 2009; Perfetti and Tan, 2013; Tan et al., 2005). Specifically, Chinese characters are composed of intricate strokes packed into a square shape and their phonologies are mainly accessed through whole-word mapping (i.e., addressed phonology), whereas English words are constructed by linear combinations of letters and their phonologies are mainly accessed through grapheme-to-phoneme mapping (i.e., assembled phonology). Given their differences in visual appearance and orthographic transparency, reading Chinese words relative to English words may involve more visuospatial analysis and more whole-word processing, and consequently recruit more regions in the right hemisphere (Mei et al., 2013; Tan et al., 2000). In support of this view, previous studies have reported bilateral (e.g., Guo and Burgund, 2010; Liu et al., 2007; Peng et al., 2004; Tan et al., 2001; Wang et al., 2011; Wu et al., 2012) or even right-lateralized activation (Tan et al., 2000) in the occipitotemporal region for Chinese

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processing. This is in clear contrast to the left-hemispheric dominance in the processing of English words (Cohen et al., 2002; Price, 2012; Vigneau et al., 2005). In a direct comparison between native Chinese and native English speakers, Nelson et al. (2009) confirmed that English speakers showed left-lateralized activation in the occipitotemporal region when reading English words, while Chinese speakers activated the bilateral occipitotemporal region when reading Chinese words.

Given the differences in occipitotemporal laterality between Chinese and English reading, how does Chinese experience affect English reading? To our knowledge, only one study has addressed this question by comparing Chinese–English bilinguals with native English speakers (Nelson et al., 2009). They found that Chinese–English bilinguals activated the bilateral fusiform cortex when processing Chinese and English words. These results supported the idea that long-term experience with Chinese language shapes fusiform laterality of English processing. This pioneering study, however, had three important limitations. First, Nelson et al.'s study included a relatively small sample size (i.e., 11 Chinese–English bilinguals and 6 native English speakers), which might greatly be affected by intersubject variances (Dehaene et al., 1997). Second, their study relied on the comparison between native English readers and native Chinese readers who learned English as a second language, which might have been confounded by factors such as language proficiency and age of acquisition, two factors that have been found to have significant effects on the neural mechanism of reading (e.g., Chee et al., 2001; Hernandez and Li, 2007). One way to control for those two confounding factors is to compare English reading between two groups of native English speakers, those with and those without Chinese experience. Finally, their study did not examine the laterality differences across different subregions in the occipitotemporal cortex. It has been suggested the anterior and posterior parts of the occipitotemporal region are engaged, respectively, in lexico-semantic versus visuo-perceptual processing (e.g., Simons et al., 2003; Xue and Poldrack, 2007), and high-level orthographic versus low-level perceptual processing (e.g., encoding letter shapes) (Vinckier et al., 2007). Consequently, functional asymmetry in the anterior and posterior occipitotemporal regions is sensitive to high-level linguistic (e.g., semantic) and visuospatial factors, respectively (Mei et al., 2013; Seghier and Price, 2011). Consistently, our previous study revealed that functional laterality of Chinese processing varied across different subregions in occipitotemporal cortex — left laterality in the anterior region and bilaterality in the posterior region (Xue et al., 2005). Therefore, it is important to examine fusiform laterality by its subregions.

To overcome the three limitations mentioned above, the present study 1) used a relatively large sample (42 native Chinese speakers, 44 native English speakers with experience with Chinese language, and 45 native English speakers without prior experience with Chinese language) to reduce the confounding effect of intersubject variances, 2) compared native English speakers with and without Chinese experience to avoid the confounding effect of language proficiency and age of acquisition, and 3) split the fusiform gyrus into three subregions (i.e., anterior, middle, and posterior) to examine the effect of Chinese experience on the functional laterality of English reading in different fusiform subregions. To minimize (or avoid) automatic activation of Chinese during English reading, we used an implicit reading task (i.e., a passive viewing task) and included both English words and alphabetic pseudowords, the latter of which were not likely to activate Chinese processing automatically because they had no semantics and hence could not be translated into Chinese words. In this study, we first confirmed the laterality differences between Chinese and English by comparing native Chinese speakers with native English speakers without prior experience with Chinese language. We then examined whether long-term experience with Chinese language shaped the functional asymmetry of English reading in different fusiform subregions by comparing fusiform laterality in English speakers with vs. those without experience with Chinese language.

Methods

Subjects

Eighty-nine native English speakers (34 males, mean age = 20.72 ± 2.02 years old) and 42 native Chinese speakers (21 males; 22.05 ± 1.85 years old) participated in this study. Native English speakers included two groups: those with long-term experience with Chinese language (n = 44) and those without (n = 45). The former group included mostly Chinese Americans who were born in United States but had learned Chinese for at least ten years. Among the latter group of 45 subjects, none had any previous experience with Chinese language or other logographic languages such as Japanese, but 29 of them learned other alphabetic languages (e.g., French, Spanish, German, and etc.) as a second language (typically in high school because of the second-language requirements) and the remaining 16 subjects considered themselves as monolingual English speakers because of their minimal fluency in another language.

The two groups of native English speakers did not differ in nonverbal intelligence (Raven's Advanced Progressive Matrices) (Raven, 1990) and performance on English reading tasks [word identification from the Woodcock Reading Mastery Tests — Revised (WRMT-R) (Woodcock, 1987), phonemic decoding efficiency and sight word efficiency from the Test of Word Reading Efficiency (TOWRE) (Torgesen et al., 1999), rapid object and color naming from the Comprehensive Test of Phonological Processing (CTOPP) (Wagner et al., 1999)] (Table 1).

All subjects had normal or corrected-to-normal vision, had no previous history of neurological or psychiatric disease, 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 participants before the experiment. This study was approved by the IRBs of the University of California, Irvine, the University of Southern California, and Beijing Normal University.

Materials

Sixty English words, 60 alphabetic pseudowords (i.e., letter strings that comply with English orthographic rules, such as *hilk* and *bime*), and 60 Chinese words were used in this study. The English materials were presented in gray-scale with 226 × 151 pixels in size, and the Chinese words were 151 × 151 pixels in size.

All English words were monosyllables. They were selected from the MRC psycholinguistic database: machine usable dictionary, version 2.00

Table 1
Mean scores (and SD) on the reading tests and a nonverbal intelligence test obtained by native English speakers with or without Chinese experience.

	With Chinese experience	Without Chinese experience	*t*	*p*
Word identification	99.39 (4.13)	98.02 (4.16)	1.55	.125
Sight word efficiency	98.32 (6.93)	98.26 (6.85)	0.04	.966
Phonemic decoding efficiency	57.05 (5.41)	55.87 (5.24)	1.03	.304
Rapid object naming	41.20 (6.14)	40.75 (7.71)	0.31	.761
Rapid color naming	37.35 (5.76)	37.38 (5.80)	0.03	.977
Raven's Advanced Progressive Matrices	26.64 (4.42)	25.58 (4.21)	1.16	.250

Note: the scores for rapid object and color naming are amounts of time (second) needed to complete the tests, and the scores for other tests are the number of correct items. Word identification is a subtest of the Woodcock Reading Mastery Tests — Revised (WRMT-R); sight word efficiency and phonemic decoding efficiency are subtests of the Test of Word Reading Efficiency (TOWRE); rapid object and color naming are subtests of the Comprehensive Test of Phonological Processing (CTOPP).

(Wilson, 1988). We chose medium- to high-frequency (i.e., more frequent than 10 per million words) words with a mean frequency of 530.80 per million words (SD = 740.98) to ensure that they were familiar to Chinese subjects. All English words consisted of 3–6 letters (mean = 4.38, SD = 0.85). Monosyllabic alphabetic pseudowords, which matched the real words in number of letters (mean = 4.38, SD = 0.85), were selected from the ARC nonword database (Rastle et al., 2002).

All Chinese words were medium- to high-frequency characters according to the Chinese word frequency dictionary (Wang and Chang, 1985). On average, they occurred at the rate of 498.50 per million words (SD = 548.12). The words consisted of 2–9 strokes (mean = 5.98, SD = 1.41) and 2–3 units (mean = 2.70, SD = 0.46) (Chen et al., 1996).

FMRI task

We used an implicit reading task (i.e., a passive viewing task) for the fMRI scan. The passive viewing task has an advantage of not being confounded by factors such as task difficulty (Chen et al., 2007; Cohen et al., 2002; Xue et al., 2006a, 2006b). It included three types of stimuli, namely English words, alphabetic pseudowords, and Chinese words. Stimulus presentation and response data collection were programmed using Matlab (Mathworks) and the Psychtoolbox (www.psychtoolbox.org). Rapid event-related design was used, with the stimuli pseudo-randomly mixed. Trial sequences were optimized with OPTSEQ (http://surfer.nmr.mgh.harvard.edu/optseq/) to improve design efficiency (Dale, 1999).

Subjects performed two runs of the passive viewing task. In each run, each word lasted for 600 milliseconds, with a jittered inter-stimulus interval varying randomly from 1.4 to 6.4 s (mean = 1.9 s) to improve design efficiency. Subjects were asked to carefully view the stimuli. To ensure that subjects were awake and attentive, we instructed subjects to press a key whenever they saw an underlined word. This happened 6 times per run. Subjects correctly responded to more than 10 of the 12 underlined words across the two runs, suggesting that subjects were attentive to the stimuli during the passive viewing task.

MRI data acquisition

Imaging data of Chinese speakers were acquired with a 3.0T Siemens MRI scanner in the MRI Center at Beijing Normal University, and those of English speakers were acquired with a 3.0T Siemens MRI scanner in the Dana & David Dornsife Cognitive Neuroscience Imaging Center at the University of Southern California. A single-shot T2*-weighted gradient-echo EPI sequence was used for functional imaging acquisition with the following parameters: TR/TE/θ = 2000 ms/25 ms/90°, FOV = 192 × 192 mm, matrix = 64 × 64, and slice thickness = 3 mm. Forty-one contiguous axial slices parallel to the AC–PC line were obtained to cover the whole cerebrum and part of the cerebellum. Anatomical MRI was acquired using a T1-weighted, three-dimensional, gradient-echo pulse-sequence (MPRAGE) with TR/TE/θ = 2530 ms/3.09 ms/10°, FOV = 256 × 256 mm, matrix = 256 × 256, and slice thickness = 1 mm. Two hundred and eight sagittal slices were acquired to provide a high-resolution structural image of the whole brain.

Image preprocessing and statistical analysis

fMRI data were processed using FEAT (fMRI Expert Analysis Tool) Version 6.00, a tool in the FMRIB's software library (www.fmrib.ox.ac.uk/fsl). The first three volumes in each time series were automatically discarded by the scanner to allow for T1 equilibrium effects. The remaining images were then realigned to compensate for small head movements (Jenkinson and Smith, 2001). Translational movement parameters never exceeded 1 voxel in any direction for any subject or run. All data were spatially smoothed using a 5-mm full-width-half-maximum Gaussian kernel. The smoothed data were then filtered in the temporal domain using a nonlinear high-pass filter with a 60-s cutoff. A 2-step registration procedure was used whereby EPI images were first registered to the MPRAGE structural image, and then into the standard (Montreal Neurological Institute [MNI]) space, using affine transformations with FLIRT (Jenkinson and Smith, 2001) to the avg152 T1 MNI template.

At the first level of analysis, the data were modeled with the general linear model within the FILM module of FSL for each subject and each run. Events were modeled at the time of the stimulus presentation. These event onsets and their durations were convolved with canonical hemodynamic response function (double-gamma) to generate the regressors used in the general linear model. Temporal derivatives and the 6 motion parameters were included as covariates of no interest to improve statistical sensitivity. Null events (i.e., fixation) were not explicitly modeled, and therefore constituted an implicit baseline. Three contrast images (English words − baseline, alphabetic pseudowords − baseline, and Chinese words − baseline) were computed for each run and for each subject.

A second-level model (fixed-effects model) was constructed to average across the two runs for each participant. The data from the second-level analyses were then averaged across the subjects in the third-level analyses using a random-effects model (treating subjects as a random effect) with FLAME stage 1 only (Beckmann et al., 2003; Woolrich et al., 2004). The activation differences between English speakers with and without Chinese experience were computed using two-sample T tests. Unless otherwise indicated, group images were thresholded with a height threshold of $z > 2.3$ and a cluster probability of $P < 0.05$, corrected for whole-brain multiple comparisons using the Gaussian random field theory (Worsley, 2001).

Region of interest analysis

The fusiform gyrus was defined as the region of interest (ROI) because of its crucial involvement in visual word processing (Cohen and Dehaene, 2004; Cohen et al., 2002; Dehaene and Cohen, 2011) and its laterality differences between Chinese and English processing (Tan et al., 2000). Following Xue and Poldrack (2007), we split the left fusiform region into three smaller equal-sized regions, namely the anterior (MNI center: −40, −48, −18), middle (MNI center: −40, −60, −18), and posterior fusiform regions (MNI center: −40, −72, −18). It should be noted that the center of the left middle fusiform region is close (a little posterior) to the visual word form area (VWFA: −42, −57, −15) identified by Cohen et al. (2002). Each ROI was defined as a sphere of 6 mm radius around the center. The right homologues of those regions were also defined. The definition of all ROIs was independent of the tasks and the subjects.

ROI analyses were performed by extracting parameter estimates (betas) of each event type from the fitted model and averaging across all voxels in the cluster for each subject. Percent signal changes were calculated using the following formula: [contrast image / (mean of run)] × ppheight × 100%, where ppheight was the peak height of the hemodynamic response versus the baseline level of activity (Mumford, 2007).

We used the asymmetry index (AI) to quantify functional laterality of the three subregions of the fusiform gyrus. AI was calculated using the following formula: $AI = L - R$, where L and R represent percent signal changes in the left and right ROI, respectively (Vigneau et al., 2005). A positive AI indicates left-hemispheric lateralization and a negative number indicates right-hemispheric lateralization.

Results

Differences in fusiform laterality in Chinese and English speakers during native language reading

Because the imaging data of native Chinese and native English speakers were collected with two different MRI scanners (albeit the same model and the same scanning parameters), we did not perform direct comparisons between the groups on their neural activations. Instead, we compared functional laterality by using asymmetry index (AI) to minimize potential scanner effects. Two-way ANOVA [group (native Chinese vs. native English speakers without Chinese experience) × brain region (anterior vs. middle vs. posterior fusiform regions)] showed that the group-by-region interaction was significant ($F(2,170) = 3.12$, $p < .05$) (Fig. 1). In the posterior fusiform region, Chinese speakers showed right-lateralized activation during Chinese reading, whereas English speakers showed left-lateralized activation during English reading ($F(1,85) = 5.91$, $p < .05$). In the middle fusiform region, there was a similar trend, but it was not statistically significant ($F(1,85) = 2.05$, *n.s.*). In the anterior fusiform region, both native Chinese and native English speakers showed left-lateralized activation and did not differ in functional laterality ($F(1,85) = 0.34$, *n.s.*). These results suggest that Chinese and English processing differ in laterality in the posterior fusiform gyrus.

Long-term experience with Chinese language modulated fusiform laterality of English reading

To examine whether long-term experience with Chinese language shapes the neural mechanisms of English reading, we compared the neural activation of English speakers with and without Chinese experience. Because these data were collected with the same scanner, we first directly compared activation patterns across groups. When reading English words, the group with Chinese experience showed more activation in the right posterior fusiform region (extending to the inferior occipital gyrus) than the group without Chinese experience (Fig. 2A & Table 2). None of the regions showed greater activation for the group without Chinese experience. Similar results were found for pseudowords: The group with Chinese experience showed greater activation in the right posterior fusiform region (extending to inferior occipital gyrus) and superior occipital gyrus than the group without Chinese experience, and the latter group did not show greater activation in any of the regions (Fig. 2B & Table 2).

Next, we compared the AI with two-way (group x region) ANOVAs. Results showed that, for English word reading, there was a significant region-by-group interaction ($F(2,174) = 8.27$, $p < .001$) (Fig. 3A). Follow-up simple effects analyses revealed that, in the posterior fusiform region, the group without Chinese experience showed left-lateralized activation, whereas the group with Chinese experience showed right-lateralized activation ($F(1,87) = 10.60$, $p < .01$). In the anterior and middle fusiform regions, both groups showed left-lateralized activation and did not differ in functional laterality (anterior: $F(1,87) = 0.77$, *n.s.*; middle: $F(1,87) = 0.02$, n.s.).

Similar results were found for pseudoword reading (Fig. 3B). The region-by-group interaction was also significant ($F(2,174) = 5.41$, $p < .01$). Simple effect analyses showed that the group without Chinese experience showed left-lateralized activation in the posterior fusiform region, whereas the group with Chinese experience showed right-lateralized activation ($F(1,87) = 10.82$, $p = .001$). Both groups showed left-lateralized activation in the anterior and middle fusiform regions (anterior: $F(2,174) = 0.22$, *n.s.*; middle: $F(2,174) = 1.24$, n.s.).

Although tangential to our study, we further compared the activation and laterality patterns of English words with those of pseudowords. Consistent with previous studies (e.g., Mechelli et al., 2003; Paulesu et al., 2000), there were greater activations in the left inferior frontal gyrus and the bilateral occipitotemporal regions for pseudowords relative to words, and the activation patterns did not differ across the two groups of English speakers (Fig. 4). No regions showed more activation for words. More importantly, two-way (word type × region) ANOVAs showed that the laterality patterns in the three fusiform subregions did not differ significantly between words and pseudowords for either group of English speakers (with or without Chinese language

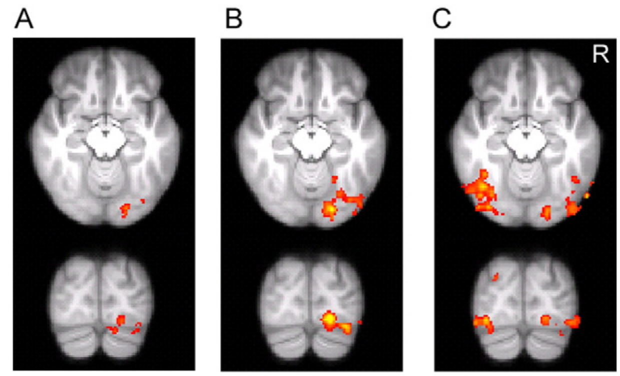

Fig. 2. Brain regions showing greater activation for English speakers with Chinese experience than those without Chinese experience when reading English words (A), alphabetic pseudowords (B), and Chinese words (C). R = right.

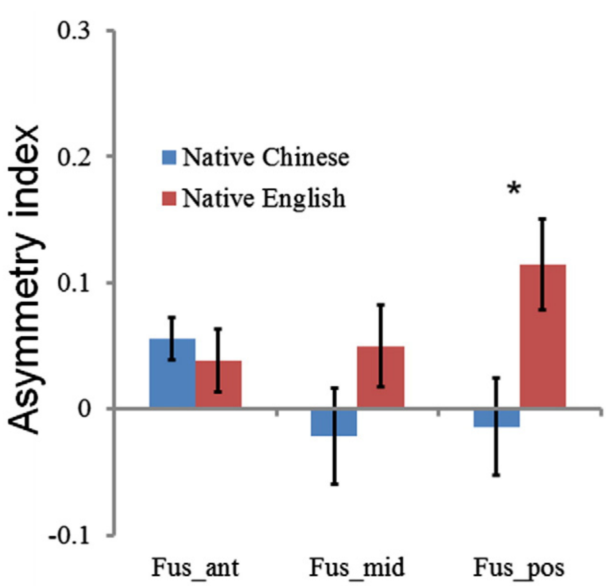

Fig. 1. Functional laterality in the anterior, middle, and posterior fusiform regions for native Chinese and native English speakers. Asymmetry index (AI) was calculated by subtracting the neural activity in the right region from that in the left region. Error bars represent the standard error of the mean. Fus_ant = anterior fusiform region; Fus_mid = middle fusiform region; and Fus_pos = posterior fusiform region. * p < .05.

Table 2
Brain regions showing more activation for the group with Chinese experience than for the group without Chinese experience.

Brain regions	x	y	z	Z	Cluster size
English words					
Right fusiform gyrus/inferior occipital gyrus	20	−86	−14	3.14	359
Alphabetic pseudowords					
Right fusiform gyrus/inferior occipital gyrus	18	−84	−10	4.67	854
Right superior occipital gyrus/superior parietal lobule	14	−72	58	3.60	424
Right lingual gyrus	14	−84	−10	3.73	814
Chinese words					
Left fusiform gyrus/inferior occipital gyrus	−42	−64	−16	3.99	1350
Right fusiform gyrus/inferior occipital gyrus	44	−38	−30	4.25	1272
left superior occipital gyrus/superior parietal lobule	−32	−62	56	3.68	795
Right superior occipital gyrus/superior parietal lobule	20	−74	58	4.00	1166

Note: cluster size represents the number of voxels.

experience) (Fig. 3). In other words, neither the main effects nor the interaction effects were significant (the smallest $p = .141$) except the main effect of region in English speakers with Chinese language (i.e., more left-lateralized activation in the anterior and middle fusiform than the posterior fusiform regardless of word type, $F(2,86) = 8.52$, $p < .001$). Taken together the above results, we found that English speakers with Chinese experience showed similar laterality pattern to Chinese speakers (i.e., right laterality in the posterior fusiform region and left laterality in the anterior fusiform region), which was different from English speakers without Chinese experience (i.e., left laterality in all three fusiform subregions). These results suggest that long-term experience with Chinese language shapes the fusiform laterality of English reading.

To rule out the possibility that right-hemispheric laterality for English speakers with Chinese experience was due to the fact that they were bilinguals, whereas the group without Chinese experience included monolinguals, we also compared functional laterality of the bilinguals who learned another alphabetic language with monolingual English speakers. Both subgroups showed left-lateralized activation in the three fusiform subregions when reading English words and pseudowords (Fig. 5). Two-way ANOVA showed that neither main effect nor interaction were significant (all $ps > .1$).

Differences in functional laterality when reading Chinese words

Whole-brain analysis showed that reading Chinese words elicited greater activation in the bilateral occipitotemporal and occipitoparietal regions for English speakers with Chinese experience than for those without Chinese experience (Fig. 2C & Table 2). This result suggests that language experience shapes the neural activations in the bilateral fusiform gyrus.

In terms of functional laterality in the three fusiform subregions (Fig. 3C), a two-way ANOVA showed that the region-by-group interaction was not significant ($F(2,174) = 1.67, p = .192$). Nevertheless, given the previous evidence that functional laterality in the anterior fusiform subregion is affected by semantic factors (Seghier and Price, 2011), we focused on functional laterality in this subregion. Consistent with Seghier and Price's finding, the group with Chinese experience (who would know the meanings of the Chinese stimuli) showed more left-lateralized activation in the anterior fusiform region than the group without Chinese experience (to whom the Chinese stimuli had no semantics) ($F(1,87) = 4.02, p < .05$). There was a similar trend in the middle fusiform region, but it was not statistically significant ($F(1,87) = 2.00$, *n.s.*). In contrast, both groups showed right-lateralized activation in the posterior fusiform region and they did not differ significantly ($F(1,87) = 0.08$, *n.s.*).

Discussion

The present study examined whether long-term experience with Chinese language shapes the fusiform gyrus's laterality when reading English words, alphabetic pseudowords, as well as Chinese words. Three groups of subjects were used: native Chinese speakers, native English speakers with Chinese experience, and native English speakers without Chinese experience. We found that, when reading words in their respective native language, Chinese speakers and English speakers without Chinese experience differed in functional laterality in the posterior fusiform region (right laterality for Chinese speakers, but left laterality for English speakers), but not in the anterior and middle fusiform regions. More importantly, compared with the group without Chinese experience, native English speakers with Chinese experience showed more recruitment of the right fusiform cortex when reading English words and alphabetic pseudowords. Further quantitative laterality analysis (i.e., ROI analysis of asymmetry index [AI]) showed that the two groups' functional laterality differed in the posterior fusiform region, but not in the anterior and middle fusiform regions. These results suggest that long-term experience with Chinese language shapes the fusiform laterality of English reading.

Cross-language differences in laterality of the fusiform subregions

Previous neuroimaging studies have suggested that functional laterality of Chinese and English processing differs in the occipitotemporal region. Specifically, many studies have identified bilateral (e.g., Guo and Burgund, 2010; Liu et al., 2007; Tan et al., 2001; Wang et al., 2011) or even right-lateralized activation (Tan et al., 2000) in the occipitotemporal region for Chinese processing, which is in contrast with left-lateralized activation for English processing (Cohen et al., 2002; Price et al., 1996; Vigneau et al., 2005). These laterality differences have also been confirmed by direct comparisons between native Chinese and native English speakers (Nelson et al., 2009).

Our study found that the laterality differences between Chinese and English processing varied across different fusiform subregions. Specifically, cross-language differences in functional laterality were evident in the posterior fusiform region (i.e., right laterality for

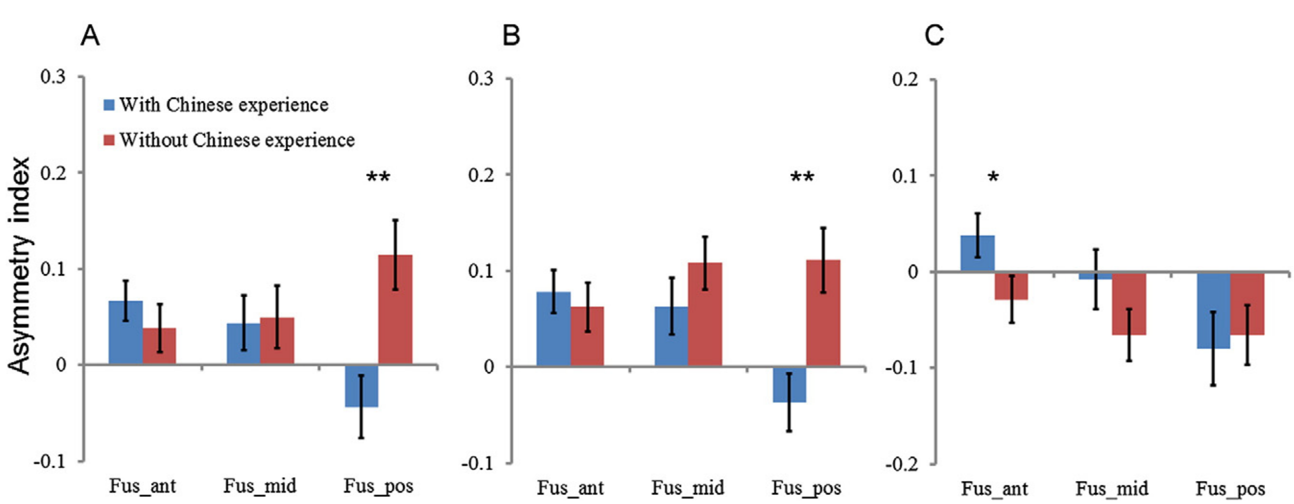

Fig. 3. Functional laterality in the anterior, middle, and posterior fusiform regions for native English speakers with or without Chinese experience when reading English words (A), alphabetic pseudowords (B), and Chinese words (C). See Fig. 1 caption for AI calculation, brain region abbreviations, and meaning of error bars. * $p < .05$ and ** $p < .01$.

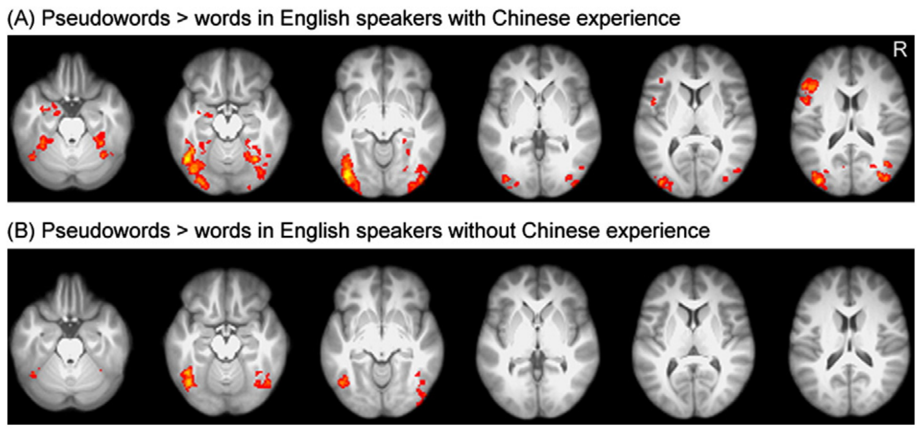

Fig. 4. Brain regions showing greater activations for pseudowords relative to words in English speakers with (A) and without (B) Chinese experience. Compared with reading words, reading pseudowords elicited greater activations in the bilateral occipitotemporal cortex for both groups of English speakers and in the left inferior frontal gyrus only for English speakers with Chinese experience. The left inferior frontal gyrus also showed greater activation for pseudowords relative to words in native English speakers without Chinese experience when a relatively liberal threshold ($Z > 2.3$, uncorrected) was used. No regions showed greater activations for words. In addition, the neural activations in the contrast of pseudowords minus words did not significantly differ across the two groups of English speakers. All activations were thresholded at $z > 2.3$ (whole-brain corrected). R = right.

Chinese processing, but left laterality for English processing), but decreased in the middle fusiform region and diminished in the anterior fusiform region. These Chinese–English differences in fusiform laterality are consistent with the posterior-to-anterior progression from processing visuoperceptual information to processing high-level linguistic (e.g., lexico-semantic) information across the occipitotemporal subregions (Bouhali et al., 2014; Danelli et al., 2013; Seghier and Price, 2011; Simons et al., 2003; Vinckier et al., 2007; Xue and Poldrack, 2007). First, the posterior fusiform region is believed to be responsible for processing visuoperceptual information (Danelli et al., 2013; Vinckier et al., 2007; Xue and Poldrack, 2007). Due to the complex visual structure and the extreme deep orthography of Chinese, reading Chinese words as compared to English words involves more visuospatial analysis and more whole-word processing, and thus requires a greater involvement of the right posterior fusiform region (Chen et al., 2009; Mei et al., 2013; Tan et al., 2000).

In contrast, the left anterior fusiform region is thought to be related to lexico-semantic processing, as shown in greater activations for words relative to pseudowords (Cattinelli et al., 2013; Mechelli et al., 2005; Taylor et al., 2013) and for semantic tasks relative to perceptual/phonological tasks (Binder et al., 2009; Price and Mechelli, 2005; Sharp et al., 2010). The semantic system should not be sensitive to differences in writing systems. Indeed we observed similar left laterality for Chinese and English in the anterior fusiform region.

Finally, in terms of the middle fusiform region, we did not observe a significant difference in functional laterality between Chinese and English reading, suggesting that this subregion is not sensitive to differences in writing systems. One explanation of this result is that this subregion's role in visual word processing is independent of script (Bolger et al., 2005), which is consistent with the VWFA hypothesis (Cohen and Dehaene, 2004; Cohen et al., 2002; Dehaene and Cohen, 2011). Indeed, as mentioned in the ROI analysis, the center of the left middle fusiform subregion defined in this study was close to the VWFA identified by Cohen et al. (2002). We should hasten to add, however, that our above explanation is tentative because the VWFA hypothesis is still being debated (Devlin et al., 2006; Price and Devlin, 2011) and because we did not include non-linguistic stimuli (or other baseline tasks) to localize the VWFA functionally and individually (Glezer and Riesenhuber, 2013; Mano et al., 2013).

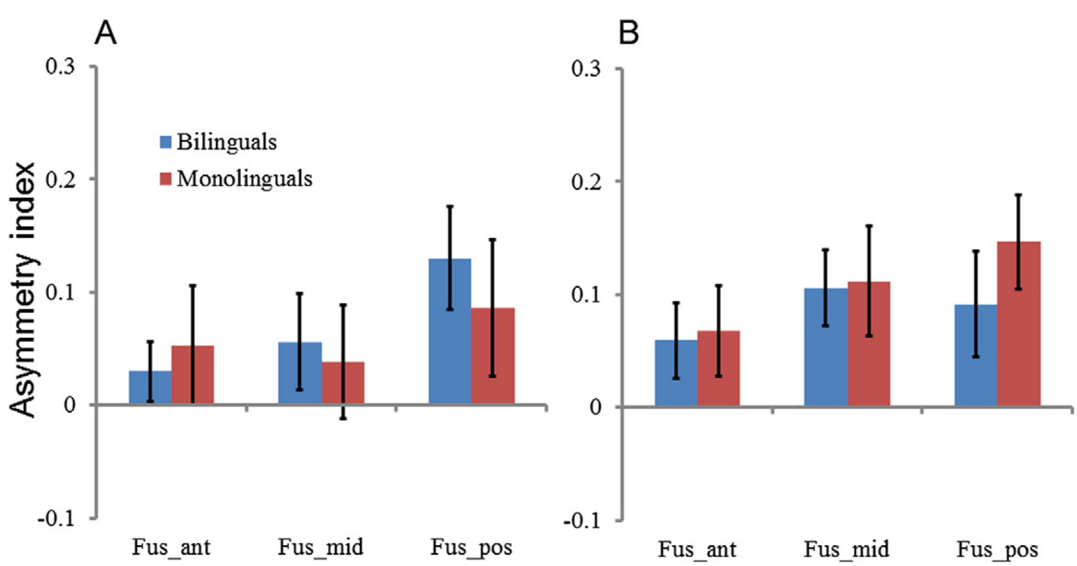

Fig. 5. Functional laterality in the anterior, middle, and posterior fusiform regions for bilinguals and monolinguals of native English speakers without Chinese experience when reading English words (A) and alphabetic pseudowords (B). See Fig. 1 caption for AI calculation, brain region abbreviations, and meaning of error bars.

Chinese experience and fusiform laterality when reading Chinese

English speakers who had learned Chinese showed left laterality in the anterior fusiform region, but right laterality in the posterior fusiform region, which is the same pattern as that for native Chinese speakers. In contrast, English speakers without Chinese experience showed right laterality in all three fusiform subregions when reading Chinese words. The results for the posterior region suggest that English speakers heavily recruited the right posterior fusiform cortex to accommodate the complex visual structure of Chinese, which is consistent with the accommodation process (Perfetti et al., 2007). The results for the anterior and middle fusiform regions confirm the importance of language experience (in this case, Chinese) in left laterality (when reading Chinese). This result is consistent with previous findings that the left fusiform cortex is more involved in reading for people with relevant language experience than for those without such an experience (Baker et al., 2007; Szwed et al., 2013), for familiar scripts than for unfamiliar scripts (Baker et al., 2007; Song et al., 2010), for unfamiliar scripts after learning than before learning (Xue et al., 2006b), and for nonverbal stimuli (e.g., faces) with verbal training than for those without verbal training (Moore et al., 2013).

Chinese experience and fusiform laterality when reading English

Our study provides direct neuroimaging evidence for the effect of Chinese learning experience on the fusiform laterality of English reading. We found that, for both English words and alphabetic pseudowords, English speakers with Chinese experience showed greater engagement of the right posterior fusiform cortex than English speakers without Chinese experience. By including alphabetic pseudowords, we were able to rule out an alternative explanation involving automatic coactivation of Chinese when reading English because pseudowords were unlikely to have triggered automatic activation of Chinese words as English words would have. These results provided direct evidence for the effect of a second language on the neural mechanisms of the native language, which complemented previous findings of the native language's influence on the neural mechanisms of a second language (Nelson et al., 2009; Tan et al., 2003).

It is worth pointing out that the two groups of native English speakers in this study differed in ethnicity (i.e., Chinese Americans for the group with Chinese experience and non-Chinese Americans for the group without Chinese experience), which might have led some people to speculate whether our findings could be attributed to any racial differences in the structure of the fusiform gyrus. Our study could not completely rule out that possibility, but existing evidence does not seem to support that speculation. Previous studies that compared brain structures of Chinese and Western samples did not observe any differences in the fusiform region (Chee et al., 2010; Crinion et al., 2009; Green et al., 2007; Kochunov et al., 2003). Such results gave us confidence that the laterality differences between the two groups of native English speakers in this study reflected the effect of long-term experience with Chinese language on English reading. Future studies should confirm our results by specifically recruiting non-Chinese Americans who have learned Chinese as a second language for many years.

Summary

The present study overcame several weaknesses (i.e., small sample size; potential confounds of second language proficiency, age of acquisition, and learning methods; and a lack of specificity within the fusiform gyrus) of previous neuroimaging research on cross-language influences. Our results revealed that Chinese and English processing differed in functional laterality in the posterior fusiform cortex and that long-term experience with Chinese shaped the fusiform asymmetry of English reading. These results provide direct neuroimaging evidence for cross-language influences and should have important implications for our understanding of cross-language influences in terms of neural organizations.

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