

## Research paper

## Functional and structural neuroplasticity associated with second language proficiency: An MRI study of Chinese-English bilinguals

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## ABSTRACT

Second language (L2) learning modulates functional and anatomical neuroplasticity, as amply demonstrated by previous studies (see Li, Legault, & Litcofsky, 2014, for review). This study, combining resting-state functional magnetic resonance imaging (rs-fMRI), task-based fMRI, and structural MRI (sMRI), examined L2 learning-induced cross-modality neural changes in Chinese-English bilinguals with low- to high-intermediate L2 proficiency. Our rs-MRI data showed a positive correlation between the participants' amplitude of low-frequency fluctuation (ALFF) and their L2 proficiency in brain areas within the salience network, implying L2 learning experience-associated cognitive flexibility. Further, fMRI data of the L2 picture naming task, compared with that of the L1 processing, displayed more neural activation in cognitive control and language control areas, and the increase correlated positively with the L2 proficiency. Finally, gray-matter volume (GMV) analyses of sMRI data revealed enlarged GMV in an extensive brain network in higher-proficiency bilinguals, which coincided with their functional changes. Our multimodal imaging data converge to support an essential role of the right fusiform gyrus in Chinese native speakers learning L2 as late non-proficient bilinguals, which may pertain to the logographic nature of their L1 Chinese. Our findings shed light on the neural plasticity of L2 learning and suggest that both L1 and L2 experiences shape the bilingual brain.

## 1. Introduction

Whether bilingual mental control of two languages may enhance cognitive control has been intensely debated recently (Green, 1998; Green & Abutalebi, 2013; Kroll & Bialystok, 2013; Liu et al., 2019; Paap, Anders-Jefferson, Mason, Alvarado, & Zimiga, 2018; Paap, Johnson, & Sawi, 2015; Sulpizio, Del Maschio, Del Mauro, Fedeli, & Abutalebi, 2020; Wang, Fan, Liu, & Cai, 2016; see Antoniou, 2019; Dong & Li, 2019; Li & Dong, 2020, for recent reviews). However, there has been ample evidence that bilingual experience induces changes in brain function, structure, and networks (e.g., Chai et al., 2016; DeLuca, Rothman, Bialystok, & Pliatskas, 2019; Klein, Mok, Chen, & Watkins, 2014; Mårtensson et al., 2012; Pliatsikas, 2019; Saidi et al., 2013; Qi, Han, Garel, San Chen, & Gabrieli,

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2015; Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010; Yang, Gates, Molenaar, & Li, 2015; Yang & Li, 2019; see Li, Legault, & Litcofsky, 2014, for review).

The past decade has witnessed a rapid growth of neuroimaging studies on L2 learning, yet results have been inconsistent across those studies. L2 age of acquisition (AoA) and L2 proficiency, as two key factors that govern how bilinguals process languages neurally (see Hernandez, 2013; Hernandez & Li, 2007), are in association with many different brain regions, whose functions remain unclear. For example, L2 proficiency has been associated with various regions, including the inferior parietal lobule (IPL) (e.g., Barbeau et al., 2017; Cornelissen et al., 2004; Della Rosa et al., 2013; Mechelli et al., 2004; Veroude et al., 2010), hippocampus (e.g., Breitenstein et al., 2005; Mårtensson et al., 2012; Opitz & Friederici, 2004), inferior frontal gyrus (IFG) (e.g., Hosoda, Tanaka, Nariai, & Hanakawa, 2013; Mohades et al., 2012; Opitz & Friederici, 2003; Yang & Li, 2012), insula (e.g., Chee, Soon, Lee, & Pallier, 2004; Yang & Li, 2012), superior temporal gyrus (STG) (e.g., Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013; Yang & Li, 2019), fusiform gyrus (e.g., Qu et al., 2019; Xue, Chen, Jin, & Dong, 2006a), and caudate (e.g., Hosoda et al., 2013; Tan et al., 2011; Zou et al., 2012). The inconsistent findings, on the one hand, could imply that L2 proficiency is a complex construct, while on the other hand might stem from the lack of standardized protocols across labs, variability in participants' language background, different language learning processes measured using dissimilar tasks, and specific neuroimaging techniques applied in various studies.

The present study used multimodal brain imaging methods to explore the functional and structural neuroplasticity associated with L2 learning in an attempt to reveal their convergence. While most studies examined either functional or structural neural adaptation associated with L2 learning, few included multiple measures in one study. A recent exception by DeLuca, Rothman, Bialystok, and Pliatsikas (2019) examined language use-associated changes in white matter integrity, gray matter volume, and resting-state connectivity. In the current study, we examined not only task-free intrinsic brain dynamics and gray-matter volumes as in DeLuca et al. (2019) but also L2 proficiency-related neural changes in task-related brain activation. In this way, we hope to reveal some invariant biomarkers for L2 improvement. As bilingualism reflects a spectrum of experience instead of a categorical variable, we used regression analyses to examine the L2 proficiency-related neuroplasticity in late unbalanced bilinguals, whose L2 proficiency levels varied from low to high-intermediate levels.

Previous research on L2 learning-induced neural changes has mainly focused on bilinguals of alphabetic languages or learners of alphabetic languages. A few studies that have examined English speakers learning a logographic language, such as Chinese (e.g., Qi et al., 2019; Wong et al., 2008; Yang et al., 2015) showed distinct patterns. Wong, Perrachione, and Parrish (2007) reported training-related increased activation in the left posterior STG, while Yang et al. (2015) revealed decreased brain activation in the temporal and occipital regions of American monolinguals after they took a 6-week training on Chinese pseudowords. More recently, Qi et al. (2019) trained English speakers in a 4-week Mandarin course and found increased activation in left IFG and left superior parietal lobule (SPL), which did not correlate with L2 proficiency. None of the above studies of Chinese learning showed functional or neural changes in the left IPL, a hub previously implicated in L2 learning of alphabetic languages, especially for the learning of L2 vocabulary (e.g., Cornelissen et al., 2004; Della Rosa et al., 2013; Mechelli et al., 2004; Veroude et al., 2010).

Several other studies that have examined L2 learning in Chinese speakers suggest that increased L2 proficiency is associated with activity in the fusiform gyrus. Activation in the fusiform gyrus has been reported for the reading of alphabetic scripts (e.g., Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003) and has been regarded as the visual word form area (VWFA) in many languages, including Chinese (e.g., Tan, Laird, Li, & Fox, 2005). Unlike those studies on L1 processing, Xue et al. (2006a) found the unique role of fusiform gyrus in L2 learning. They trained 12 Chinese adults to learn 120 Korean characters in two weeks and found that better L2 learning performance was associated with a leftward cerebral asymmetry in the fusiform areas. Further, Xue, Chen, Jin, and Dong (2006b) revealed that visual form training significantly decreased the activation of the bilateral fusiform cortex and the left inferior occipital cortex. In contrast, phonological training increased activation in these regions, and the right fusiform remained more active after semantic training. The authors suggest that visual, phonological, and semantic learning experiences change the fusiform gyrus in Chinese speakers who learn a new language. The critical role of fusiform gyrus in Chinese speakers' L2 learning was further highlighted in Qu et al. (2017). The authors revealed neural pattern similarity in the left pars opercularis and fusiform before artificial language learning in Chinese speakers correlated with their naming latency of the learned words after training.

To verify whether the contribution of fusiform gyrus is specific to Chinese speakers or Chinese learning experience, Mei et al. (2015) compared Chinese speakers and English speakers with or without Chinese experience and found right laterality in the posterior fusiform gyrus for Chinese speakers, but left laterality for English speakers. English speakers with Chinese experience showed more recruitment of the right posterior fusiform gyrus compared with English speakers without Chinese experience when performing English reading task. Therefore, it seems that the long-term learning experience of Chinese is associated with the fusiform gyrus. Cao, Wang, Sussman, Yan, Spray, and Rios (2019) recently validated this hypothesis by examining the influence of L1 reading experience on the neural correlates for L2 learning under speech-based learning and handwriting-based learning conditions. While English speakers showed greater functional connectivity among phonological regions in the handwriting conditions compared with the speech-based conditions, Chinese speakers with higher L1 reading ability had more connections between the right fusiform gyrus and phonological regions in the handwriting condition. Since both groups learned the same Spanish words, the different neural correlates for their discrepancy might reflect their distinct L1 learning experiences. Chinese speakers learned artificial words using Chinese handwriting-based learning approach and the visual complexity of Chinese logographic characters might engage more of the fusiform gyrus for visuo-orthographic analysis than phonological-based learning methods typically applied in alphabetic language learning.

While most of these studies implicating the role of fusiform gyrus used task-related functional neuroimaging methods, few studies explored the structural basis and default functionality at rest. In a large-scale MRI study, Zhang et al. (2013) examined 226 Chinese participants when they read Chinese, English, and alphabetic pseudowords (reading tasks), compared with a visual-auditory learning task (non-reading task). They found that the cortical thickness of their left mid-fusiform gyrus was positively correlated with their

performance in the reading tasks. The authors highlighted the role of left fusiform cortex in reading. However, Luo et al. (2019), using quantitative MRI (qMRI) combined with fMRI, found that the left middle fusiform gyrus is associated with the L2 AoA effect, but not with the L2 proficiency effect. With respect to resting-state fMRI, a recent study by Sun, Li, Ding, Wang, and Li (2019) used rs-fMRI to study the effect of L2 proficiency on cognitive control network during resting-state. Their results showed significant group difference between high- and low-proficiency bilinguals in their resting-state network for cognitive flexibility and inhibition, but not in the network of working memory. While some studies include several measures to investigate L2 proficiency-related neuroplasticity (e.g., DeLuca et al., 2019; Nichols & Joanisse, 2016), most studies focused on one type of adaptation, such as functional changes, structural neuroplasticity, or intrinsic functional connectivity changes. An analysis that can combine those measures to capture the consistent relationship between L2 proficiency and neuroplasticity could clarify the inconsistency in the current literature. The present study addresses this call by examining the neuroplasticity associated with L2 proficiency using multimodal imaging approaches. We identified L2 proficiency-related brain changes in late Chinese-English bilinguals, who were low to high-intermediate proficiency bilingual and underwent resting-state fMRI (rs-fMRI), task-based fMRI, and structural MRI (sMRI) scans.

The rs-fMRI, which is free of task performance, shows the intrinsic brain dynamics as well as individual-specific features (Gordon et al., 2017). In the present study, we used ALFF (amplitude of low-frequency fluctuation), an index of rs-fMRI, as it is a data-driven, voxel-wise, and frequency-based measure of low-frequency BOLD fluctuations (0.01–0.1 Hz). It has been proved to be a significant predictor for brain activity and behavioral performance in a variety of cognitive tasks, such as the midline cingulate activation in Flanker task (Mennes et al., 2011), semantic processing efficiency in object conceptual processing task (Wei et al., 2012), and left STG activation and learning performance after spoken language learning (Deng, Chandrasekaran, Wang, & Wong, 2015). With respect to L2 proficiency-related rs-fMRI, we predict greater extent of engagement of cognitive flexibility in basal ganglia at resting-state. With respect to neuroplasticity associated with task-based fMRI, we assessed L2 proficiency-related brain changes in L1 and L2 picture naming tasks. Based on the suggestions of Perfetti, Liu, Fiez, and Nelson (2007) that L2 learning includes accommodation of the L1 network and assimilation of the L2 network, we predict that L2 proficiency increase is associated with more involvement of English processing-related regions, such as the left IPL, and Chinese-processing-related regions, such as the left fusiform gyrus. Specifically, our late and unbalanced Chinese-English bilinguals with a low to high-intermediate proficiency level of L2 rely on L1 semantic translations to access L2 lexical items, so visual orthographic analysis that is vital for Chinese character processing is heavily involved in L2 picture naming task. Since the fusiform gyrus is the key region for visual word form analysis, especially the right fusiform gyrus for Chinese (e.g., Cao et al., 2019; Mei et al., 2015), we also hypothesize that L2 proficiency might be associated with functional changes in the fusiform gyrus, particularly the right fusiform gyrus as their L2 learning relies on L1 and therefore their L2 learning-induced neural adaptation may be constrained by their neural correlates for L1 processing. Finally, gray-matter volumes of the participants were examined to provide structural evidence to corroborate with functional associations. We hypothesize that structural changes correspond to functional changes observed in rs-fMRI and task-based fMRI and provide anatomical evidence for those functional changes. Such results based on our task-related and task-free neuroimaging data on brain function and structure will enhance our current understanding of the neural mechanisms for L2 learning and neuroplasticity.

## 2. . Methods

### 2.1. Participants

Thirty Chinese-English bilinguals (10 men; mean age  $\pm$  standard deviation = 21.64  $\pm$  1.34 years) at the Guangdong University of Foreign Studies participated in this study. As native speakers of Chinese (L1), they learned English (L2) at an average age of 7.27 (SD = 2.00) and therefore were late bilinguals. Their English proficiency levels were assessed using the paper-and-pen version of the Oxford Quick Placement Test (QPT) (Geranpayeh, 2003), a standardized comprehensive English test, and their language background was examined using the Language History Questionnaire (LHQ 2.0) (Li, Zhang, Tsai, & Puls, 2014), in which self-ratings on AoA, language proficiency, and language exposure (summarized in Table 1) are provided by participants. Their scores in QPT test (Mean = 38.47, SD = 9.24, range: 29–56), showing individual differences within our group of participants, significantly and positively correlated with their self-reports on English reading ( $r = 0.422$ ,  $p < .05$ ), writing ( $r = 0.527$ ,  $p < .01$ ), speaking ( $r = 0.426$ ,  $p < .05$ ), listening ( $r = 0.451$ ,  $p < .05$ ). Therefore their QPT scores were used to present their L2 proficiency level and the sufficient variations of QPT scores

**Table 1**

Mean and standard deviation (between brackets) of linguistic background variables in our Chinese-English participants. L1, first language (Chinese); L2, second language (English); AoA, age of acquisition.

	L1	L2
<i>Language History Questionnaire (Self-ratings)</i>		
AoA	3.83 (1.53)	7.27 (2.00)
Listening (score range: 1~7)	6.87 (0.35)	4.93 (0.83)
Speaking (score range: 1~7)	6.57 (0.73)	4.90 (0.96)
Reading (score range: 1~7)	6.73 (0.58)	5.70 (0.88)
Writing (score range: 1~7)	6.77 (0.57)	5.13 (0.73)
Years of learning	17.60 (1.87)	13.83 (2.15)
Language exposure (% per week)	48.67 (19.16)	17.20 (14.05)
Quick Placement Test (English proficiency test, score range: 0~60)		38.47 (9.24)

allowed us to run regression analyses using this variable of L2 proficiency. All participants were free of neurological disorders and were right-handed based on their responses to the handedness questionnaire by Snyder and Harris (1993). They gave written informed consent and received payment for their participation. This fMRI study was approved by the Human Research Ethics Committee for Non-Clinical Faculties at the School of Psychology of South China Normal University.

## 2.2. Materials

The experimental material consisted of 96 black and white line-drawings for concrete non-living objects selected from the UCSD International Picture Naming Project (IPNP) picture database (<http://crl.ucsd.edu/~aszekely/ipnp/>) (Bates et al., 2003). They were visually presented to the participants in picture naming fMRI tasks. The Chinese names of the objects in the pictures corresponded to two-to-three-character Chinese words and their English equivalents were either monosyllabic or bisyllabic words with 3–7 letters. All the stimuli corresponded to high-frequency words in both Chinese (Liu, Hao, Li, & Shu, 2011) and English (Brysbaert & New, 2009), matched for word frequency ( $t_{95} = 0.4$ ,  $p = .69$ ).

## 2.3. Procedure

### 2.3.1. Resting-state fMRI session

Before the picture naming task, all participants completed an 8-min rs-fMRI scanning session in which they were asked to relax and lie still in the scanner while looking at a fixation cross on the screen and keeping awake (e.g., Fox et al., 2005).

### 2.3.2. Picture naming fMRI session

As shown in Fig. 1, participants named pictures in Mandarin Chinese (L1) and English (L2), respectively, in two separate fMRI sessions. In each session (lasting 6 min and 36 s), 48 trials were presented in a pseudo-random order with jittered inner-stimulus intervals optimized through OptSeq2 (<http://surfer.nmr.mgh.harvard.edu/optseq/>) (Dale, 1999). In each trial, a color frame was presented for 500 ms, and then a picture of an object appeared in the center of the color frame for 3000 ms, followed by a blank screen for 500 ms (see Li, Yang, Suzanne Scherf, & Li, 2013 for a detailed description of this procedure). Participants were asked to name the pictures as quickly and accurately as possible within the 3500 ms. The naming language was cued by the colored frame. Specifically, the red color frame served as a cue for naming in Mandarin Chinese, and green for naming in English (see Li et al., 2013). To reduce head movements in picture naming fMRI task, we collected the participants' naming responses with the same task outside the scanner two weeks after the fMRI sessions by the operation employed in Zou et al. (2012).

## 2.4. MRI acquisition

All MRI images were acquired on a Siemens 3.0T TrioTim scanner using a 12-channel head coil at the South China Normal University, China. Functional MRI data of both picture naming fMRI sessions were collected using a T2-weighted EPI sequence gradient-echo EPI sequence (TR = 2000 ms; TE = 30 ms; flip angle = 90°; matrix size = 64 × 64; slices = 32; FOV = 192 mm × 192 mm; thickness = 4 mm, interleaved excitation). A total of 198 scans were obtained from each participant in the picture naming scanning session of each language. Functional images at rest were obtained following the same scanning protocols. During the resting-state scanning session, 240 scans were obtained for each participant. High-resolution T1-weighted images acquired from a 3D Magnetization Prepared Rapid Gradient Echo (MP-RAGE) sequence were used as anatomical references and for VBM analysis (TR = 1900 ms; TE = 2.52 ms; slice thickness = 1 mm; image matrix = 256 × 256; flip angle = 30°; FOV = 256 mm × 256 mm, interleaved excitation). A total of 176 structural scans were collected for each participant.

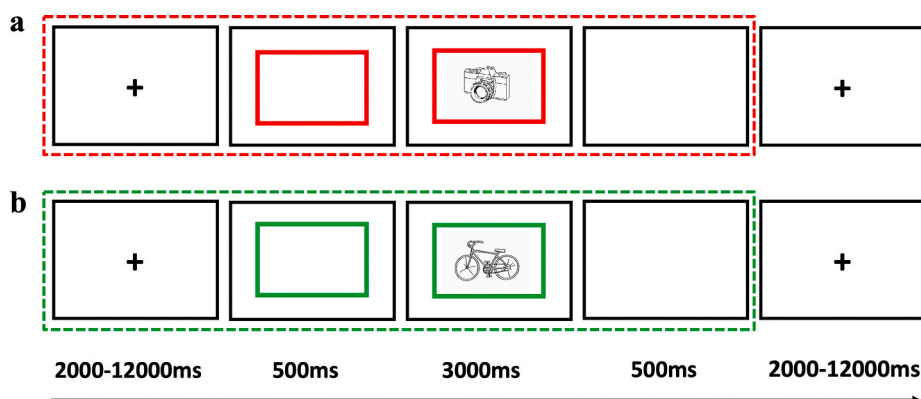
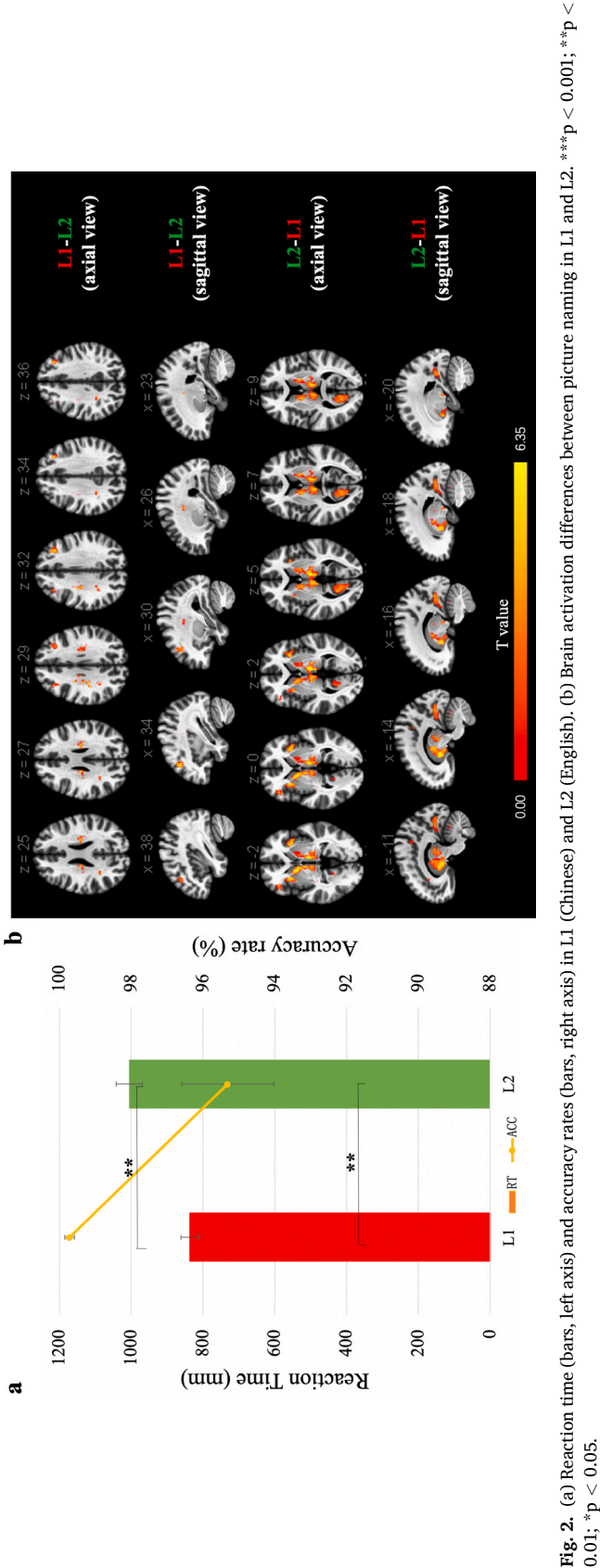


Fig. 1. Picture naming tasks in (a) L1 (Chinese) and (b) L2 (English) fMRI scans.



**Fig. 2.** (a) Reaction time (bars, left axis) and accuracy rates (bars, right axis) in L1 (Chinese) and L2 (English). (b) Brain activation differences between picture naming in L1 and L2. \*\*\* $p < 0.001$ ; \*\* $p < 0.01$ ; \* $p < 0.05$ .



## 2.5. Data analyses

### 2.5.1. Resting-state fMRI data

In the current study, for each participant's rs-fMRI scan, we calculated ALFF to show their brain's regional spontaneous neural activity (for details, see Zuo et al., 2010). Using Dpabi (DPABI V3.1) (Yan, Wang, Zuo, & Zang, 2016) implemented on Matlab (MATLAB, 2010), we discarded the first 10 volumes and preprocessed the remaining 230 volumes of each participant's resting-state data in the following preprocessing procedures: slice-timing, realignment, coregistration to structural images, normalization, and smoothing with a 6-mm Gaussian kernel. We then performed signal linear detrending, band-pass filtering (0.01–0.1 Hz), and regressed out the nuisance covariates (head motion profiles derived from the Friston 24-parameter model, white matter signal, and cerebrospinal fluid signal) within each voxel in the whole brain. We did not regress out the global signal in this study considering global signal regression may introduce biases in results – a controversial issue in rs-fMRI studies (Murphy, Birn, Handwerker, Jones, & Bandettini, 2008; Saad et al., 2012). One participant with over 3 mm of displacement and 3° of rotation in max head motion was excluded from further statistical analyses.

For each participant's rs-fMRI scans, we derived individual-level ALFF maps and then entered their standardized zALFF maps into the group-level analysis. We performed the correlation between ALFF and our bilinguals' L2 proficiency with age, sex and L2 AoA controlled as we did with the task-based fMRI and sMRI data to identify the consistent biological marker for L2 proficiency in Chinese-English bilinguals validated by the three neuroimaging methods.

### 2.5.2. Picture naming fMRI data

The fMRI data of the two picture naming sessions were also preprocessed using DPABI. The functional brain images in L1 and L2 session were preprocessed respectively in the same procedures: the first three scans of the 198 volumes collected in each language session were discarded to allow for T1 equilibration; the remaining 195 volumes were resliced to account for the acquisition time delay between different slices, realigned to the first volume for head-motion correction, co-registered to the individual anatomical images, normalized to the EPI template in the MNI space, and finally resampled into  $3\text{ mm} \times 3\text{ mm} \times 3\text{ mm}$  cubic voxels with a 6-mm kernel of Full-Width at Half Maximum (FWHM). Two participants with over 3 mm of displacement and 3° of rotation in max head motion were excluded, along with one participant discarded from resting-state data for the same reason, which left 27 participants for further statistical analyses of multimodal data.

Based on the brain activation data of each participant, group-level analyses were conducted to assess the group activation in different language conditions. Group-level brain activations corresponding to L1 and L2 conditions (in contrast to fixation) were analyzed using one-sample t-tests. Paired-samples t-tests were also conducted to assess the differences between L1 and L2 processing.

### 2.5.3. Voxel-based morphometry of sMRI data

The structural data were preprocessed using the Voxel-Based Morphometry (VBM8) toolbox in the Statistical Parametric Mapping software (SPM8; Wellcome Department of Imaging Neuroscience, University College London, <http://www.fil.ion.ucl.ac.uk/spm>) running on MATLAB. The original images were first reoriented to the anterior and posterior commissures and then entered segmentation using New Segment and DARTEL (create Templates and Normalized to MNI Space batch scripts) for realignment and normalization (including modulation) to the MNI template. Finally, the images were smoothed with a 6-mm Gaussian Kernel.

### 2.5.4. Regression analyses of L2 proficiency

To investigate the functional and structural neural plasticity associated with L2 proficiency, we performed regression analyses on brain functional and structural data entering participants' L2 proficiency (their QPT scores) as a covariate. Participant-level intrinsic brain dynamics in lower-frequency range (indexed by ALFF) were regressed with L2 proficiency. Their whole-brain neural responses in the L2 picture naming task were also modeled with L2 proficiency as a covariate of interest. We further examined gray matter volumes associated with the L2 proficiency level in a regression analysis. The effects of age, sex, and L2 AoA as nuisance covariates were all controlled in the regression models.

Group-level brain activation based on one-sample t-tests (L1, L2) and group comparisons based on paired-samples t-tests ( $L1 > L2$ ;  $L2 > L1$ ) survived an FWE-corrected cluster-level threshold of  $p < .05$  with a cluster extent of 12 voxels (single voxel:  $p < .001$ , number of voxels  $> 12$ ) corrected by AlphaSim (Jia et al., 2019). The regression analyses applied the same threshold. All the coordinates reported were all in MNI space.

## 3. Results

### 3.1. Behavioral performance in picture naming task

As shown in Fig. 2a, our 30 participants, who were late intermediate Chinese-English bilinguals, responded significantly more slowly (reaction time:  $L1 = 836.58 \pm 133.19\text{ ms}$ ;  $L2 = 1005.05 \pm 198.85\text{ ms}$ ), and less accurately (accuracy rates:  $L1 = 99.72\% \pm 0.73\%$ ;  $L2 = 95.31\% \pm 7.05\%$ ) when naming pictures in L2 than in L1 (reaction time,  $t_{29} = -5.71$ ,  $p < .001$ ; accuracy rate,  $t_{29} = 3.47$ ,  $p < .005$ ). There was no significant correlation between our bilinguals' accuracy rates or reaction time in L2 picture naming task and their L2 proficiency levels measured by the QPT ( $p > .05$ ).

### 3.2. Brain activation in picture naming tasks

One-sample t-tests of whole-brain activation revealed that picture naming in L1 evoked brain activation in the left IFG (BA 44), bilateral supplementary motor area (SMA) (BA 6), right insula, left IPL and bilateral fusiform gyri (BA 19). By contrast, picture naming in L2 recruited neural activities in the right MFG (BA 6) and IFG (BA 44), bilateral SMA (BA 6), insula, and fusiform gyri (BA 37/19). Left hippocampus gyrus, left thalamus, and bilateral cerebellum also showed significant activation during L2 processing.

As shown in Fig. 2b and Table 2, paired-samples t-tests revealed more neural responses in bilateral MFG (BA 9), left STG (BA 22), and left IPL (BA 40) in L1 picture naming than in L2 condition, while the latter displayed significantly greater brain activation in bilateral IFG, anterior cingulate gyrus (ACC), and fusiform gyri. Left calcarine gyrus and cerebellum were also more activated in the L2 condition than in L1.

### 3.3. Effect of L2 proficiency on brain function and structure neuroplasticity

Regression analyses for brain function and structure were conducted respectively, with L2 proficiency as a covariate of interest and effects of age, sex, and L2 AoA controlled (Fig. 3 and Table 3).

During L2 picture naming, participants with a higher level of L2 proficiency displayed more neural activity in the left precentral gyrus (BA 6), bilateral insula, right IPL, right fusiform gyrus, and left posterior cingulate gyrus (BA 31) compared with bilinguals with lower proficiency level of L2. We also correlated L2 proficiency with L1 picture naming fMRI data and found increased brain activation in left IFG and MFG, right fusiform gyrus and thalamus, bilateral insula, and middle occipital gyri (MOG), with L2 proficiency increases.

Rs-MRI data showed that L2 proficiency was positively correlated with ALFF in the left insula, bilateral fusiform gyri, left parahippocampal region, and right putamen, and negatively with ALFF in the right superior frontal gyrus (SFG) (BA 10) and left IPL.

With respect to L2 learning-induced structural changes, L2 proficiency was found to significantly predict expansions of gray matter volumes in bilateral frontal cortex, bilateral SMA, and premotor area, left STG and right MTG, bilateral fusiform gyri, left IPL, angular gyrus with also cerebellum and thalamus (Table 3).

Although our multimodal measures showed variance in L2 proficiency-related neuroplasticity, the data manifested overlapping areas between functional and structural data. Specifically, functional data combining task-based fMRI and rs-fMRI converged on the involvement of left insula and right fusiform gyrus. Task-free measures of rs-fMRI and sMRI both engaged bilateral fusiform gyri. Tasked-based fMRI and sMRI data highlighted L2 proficiency-related neuroplasticity in right fusiform gyrus. All the three measures indicated the important role of right fusiform gyrus in nonproficient English learners, whose L1 is Chinese.

## 4. Discussion

In the current study, we used multimodal neuroimaging methods to examine L2 learning-related neuroplasticity in late Chinese-English bilinguals with low-to high-intermediate L2 proficiency levels. While structural or functional changes have previously been observed in western language speakers who learn a new language, language learning-related neural changes across different measures remain to be understood, especially in bilinguals whose first language is a non-alphabetic language, such as Chinese. A study combining task-based fMRI, rs-fMRI, and sMRI to reveal L2 learning-related neural changes would help to resolve the existing inconsistency in literature and facilitate the current understanding of L2 learning and neuroplasticity. To fulfill this goal, we studied a

**Table 2**

Significant brain activation differences between picture naming in L1 (Chinese) and L2 (English).

Regions	L/R	BA	MNI coordinates			Voxel size	T value
			x	y	z		
L1 > L2							
Middle Frontal Gyrus	L	9	−36	33	30	20	3.86
	R	9	33	33	36	57	4.32
Superior Temporal Gyrus	L	22	−57	−21	−3	16	3.53
Inferior Parietal Lobule	L	40	−39	−30	30	74	4.42
L2 > L1							
Inferior Frontal Gyrus	L	47	−48	39	−3	68	4.17
	R	44	39	9	30	12	3.98
Anterior Cingulate Gyrus	L	32	−9	30	21	14	3.31
	R	32	9	30	24	39	4.43
Insula	L	13	−30	21	−6	968	6.35
	R	13	30	21	3	75	5.00
Fusiform Gyrus	L	37	−27	−39	−21	42	4.67
	R	37	33	−39	−21	14	3.53
Calcarine Gyrus	L	17	−15	−69	9	151	4.25
Cerebellum	L	−	0	−54	−33	61	5.00

\*L, left hemisphere; R, right hemisphere.

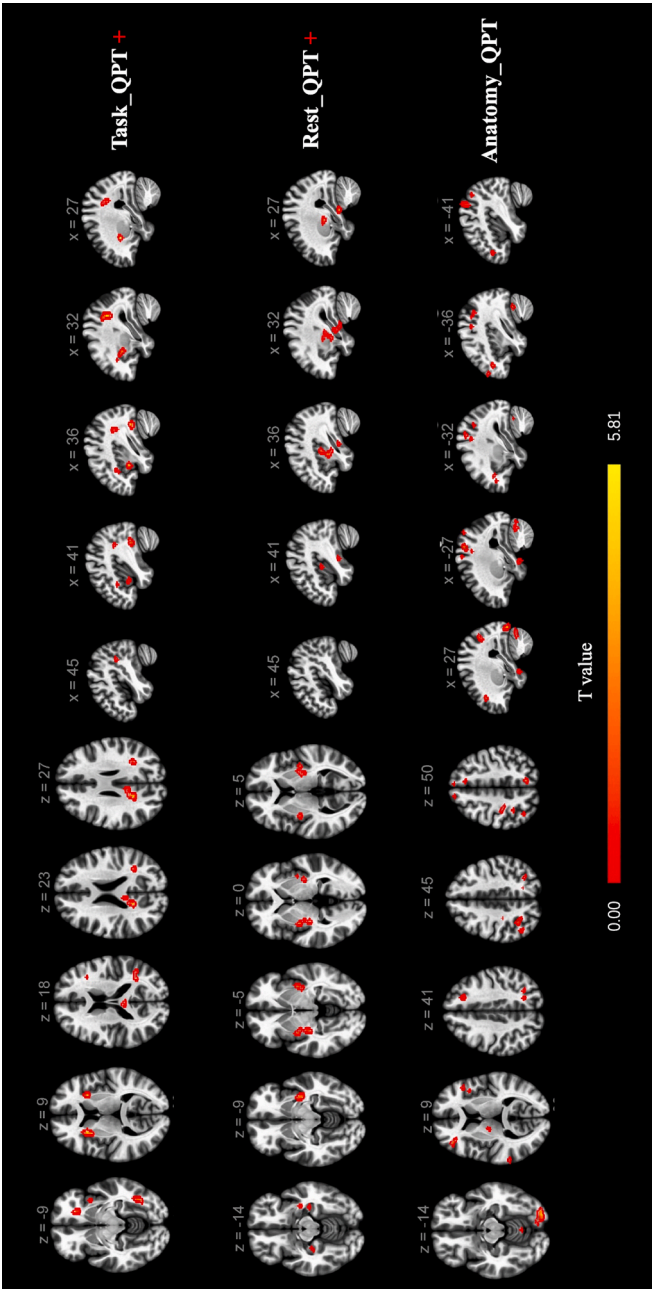


Fig. 3. Positive correlation between L2 proficiency levels and brain activation with L2 age of acquisition controlled in (a) L2 picture naming task (Task\_QPT+), (b) resting-state fMRI (Resting\_QPT+), (c) Larger gray-matter volume (GMV) with higher L2 proficiency in late nonproficient Chinese-English bilinguals. QPT, Quick Placement Test, indicating English proficiency level; +, positive correlation.



**Table 3**

Functional and structural brain regions showing significant positive correlation relationships with L2 proficiency levels of Chinese-English bilinguals with age, sex, L2 AoA effects controlled. Task-based fMRI, brain activation of L2 picture naming task; rs-fMRI, ALFF of rs-fMRI data; sMRI, gray matter volume; QPT, English proficiency level measured using Quick Placement Test; +, positive correlation.

Brain Regions	L/R	BA	MNI coordinates			Cluster size	T score
			x	y	z		
<b>Task-based fMRI_QPT+</b>							
Precentral Gyrus	L	6	−42	−6	39	20	5.16
Insula	L	13	−27	18	9	35	4.4
	R	13	27	18	9	39	4.97
Inferior Parietal Lobule	R	39	30	−48	33	63	5.07
Middle Occipital Gyrus	R	19	33	−87	24	15	3.14
Fusiform Gyrus	R	37	36	−60	−9	30	4.57
Posterior Cingulate Gyrus	L	31	−18	−48	27	53	4.7
<b>rs-fMRI_QPT+</b>							
Insula	L	13	−27	18	6	17	4.33
Fusiform Gyrus	L	20	−24	−15	−42	25	4.17
	R	20	39	−24	−21	27	3.83
ParaHippocampal Gyrus	L	35	−27	−27	−24	23	4.17
Putamen	R	−	33	−3	−6	31	3.87
<b>sMRI_QPT+</b>							
Superior Frontal Gyrus	L	8	−15	42	51	13	3.52
	R	9	26	39	24	21	4.02
Middle Frontal Gyrus	L	10	−36	56	20	22	3.72
	R	10	24	38	23	64	3.98
Inferior Frontal Gyrus	L	45	−39	44	9	144	3.63
	R	45	53	24	2	235	3.99
Supplementary Motor Area	L	6	0	−5	56	75	3.94
	R	6	14	−2	65	55	3.14
Precentral Gyrus	L	4	−26	−23	65	26	3.68
Postcentral Gyrus	L	4	−30	−35	59	100	4.31
	R	4	15	−41	60	28	3.70
Superior Temporal Gyrus	L	22	−62	−44	12	176	4.36
Middle Temporal Gyrus	R	20	44	5	−36	12	3.25
Fusiform Gyrus	L	20	−29	−14	−36	58	3.32
	R	20	33	−11	−30	224	4.14
Inferior Parietal Lobule	L	40	−44	−44	59	137	4.35
Angular Gyrus	L	39	−41	−62	48	124	3.40
	R	39	32	−63	42	18	3.52
Supramarginal Gyrus	L	40	−60	−24	29	44	3.37
Precuneus	R	7	14	−71	62	319	5.63
Superior Occipital Gyrus	R	7	26	−72	36	107	3.58
Lingual Gyrus	R	18	23	−92	−14	360	4.48
Cerebellum	L	−	−36	−65	−24	53	4.50
	R	−	27	−75	−32	170	4.09
Thalamus	L	−	−12	−8	0	14	3.25

\*L, left hemisphere; R, right hemisphere.

group of Chinese-English bilinguals who were late learners of English with low to high-intermediate proficiency levels of L2. Rs-fMRI, task-based fMRI, and sMRI data were collected from the same participants to identify the effects of L2 proficiency on intrinsic brain dynamics, functional neural substrates, and the structural brain correlates. We found that compared with L1 picture naming, L2 processing in non-fluent late Chinese-English bilinguals engaged more brain activation in language areas (e.g., bilateral IFG and insula), cognitive control areas (ACC, IPL, and cerebellum), visual-analysis area (fusiform gyri and calcarine gyrus), implying more engagement of cognitive control and visuo-orthographic analysis in addition to the compensatory help from the right homologous language areas during L2 processing compared with that during L1 processing.

In terms of L2 learning-induced neural changes, we found that functional data of rs-fMRI and task-based fMRI highlighted a positive correlation between L2 proficiency and brain activity in left insula and right fusiform gyrus. Task-free measures including rs-fMRI and sMRI data indicated the link between L2 learning and bilateral fusiform gyri. Further, task-based fMRI and sMRI data both showed L2 proficiency-related neuroplasticity in right fusiform gyrus. In all, unlike previous studies on bilinguals speaking alphabetic languages, the present multimodal neuroimaging study highlights the correlation between the right fusiform gyrus and L2 learning in Chinese native speakers who are nonproficient English learners. The following discussion presents our findings and how they indicate neuroplasticity in details.

#### 4.1. L2 learning induced functional brain changes and cognitive control

The current study showed that Chinese-English late and nonproficient bilinguals, when processing L1 (Chinese), displayed significantly more brain activation in bilateral MFG (BA9), left STG (BA 22), and left IPL (BA 40) (Table 2, Fig. 2b). MFG has been

repeatedly reported in studies of Chinese phonological, orthographic, and semantic processing (e.g., Booth et al., 2006; Kuo et al., 2004; Tan et al., 2001) and Chinese children's reading abilities are associated with brain activation in MFG (e.g., Cao, Bitan, & Booth, 2008; Siok, Perfetti, Jin, & Tan, 2004). According to Liu et al. (2006), the left MFG mediates access to Chinese phonology and semantics, and the right MFG subserves Chinese orthography processing. Therefore, the involvement of bilateral MFG in L1 processing might reflect engagement of L1 language area (left MFG) and its right homolog as a compensatory strategy. The left STG (BA 22) is responsible for phonetic feature encoding for semantic access (Mesgarani, Cheung, Johnson, & Chang, 2014), while the left IPL stores or links basic components of vocabulary knowledge (Lee et al., 2007). The greater engagement of these two areas indicates the automatic retrieval of lexical knowledge. The neural patterns shown in our bilinguals when processing their L1 is consistent with previous studies on Chinese monolinguals.

In contrast with L1 processing, L2 picture naming involved more brain activation in bilateral IFG, ACC, insula, fusiform, left calcarine gyrus, and cerebellum. The IFG has long been implicated for lexical-semantic processing and its integration with memory (Hagoort, 2005; Thompson-Schill, 2003). It is also part of the language control network: the left IFG plays a role in response inhibition, while the right IFG is associated with domain-general inhibitory control (Abutalebi & Green, 2016). ACC is involved in the conflict and error monitoring of cognitive control and has been consistently reported in language switching and selection tasks in bilinguals (e.g., Abutalebi & Green, 2007; Guo, Liu, Misra, & Kroll, 2011; Hosoda et al., 2013). Insula has been suggested to be associated with motor control of speech production: balanced bilinguals showed greater activation in insula than the unbalanced bilinguals (Chee et al., 2004). It might also work as a functional hub for canonical and non-canonical language areas, and bilateral activation of insula indicated their important mediator roles in speech and language function (Oh, Duerden, & Pang, 2014). The fusiform gyrus, known as the visual word form area, represents a prelexical representation of visual words (Dehaene, Le Clec' H, Poline, Le Bihan, & Cohen, 2002) and has been associated with visual word and face learning in Chinese speakers (Mei et al., 2010). We hypothesize that our Chinese-English bilinguals with low-to high-intermediate L2 proficiency levels rely on L1 semantic translations to access L2 lexical items, so visual orthographic analysis is heavily involved in L2 picture naming task. The calcarine gyrus, repeatedly reported in picture naming tasks, is associated with mental imagery (Klein, Paradis, Poline, Kosslyn, & Le Bihan, 2000), which corroborates our hypothesis about the involvement of fusiform gyrus mentioned. Finally, cerebellum together with subcortical structures subserves the control of action in general (Abutalebi & Green, 2016; Green & Abutalebi, 2013). In summary, L2 processing in Chinese-English nonproficient bilinguals engaged more areas of cognitive and language control, and co-activation of L1 words as a mediator of L2 lexical access.

Regression analysis of rs-fMRI data showed that L2 proficiency was positively correlated with the strength of lower-frequency brain fluctuations (ALFF) in the left insula, bilateral fusiform gyri, left parahippocampal gyrus, and right putamen. The anterior insula as part of the salience network responds to the degree of information saliency in cognitive and emotional tasks (Craig & Craig, 2009; Damasio & Carvalho, 2013; Hsu, Schloss, Clariana, & Li, 2019). According to Menon and Uddin (2010), the anterior insula and ACC form a salience network that segregates the most relevant information among internal and extrapersonal stimuli to achieve goal. The insula not only detects salient events but also initiates dynamic switching between the central executive and default-mode networks (e.g., Goulden et al., 2014; Menon & Uddin, 2010). These findings suggest the L2 learning experience provides the bilingual speakers with an opportunity to become more cognitively flexible and ready to switch (Marzecová et al., 2013; Prior & MacWhinney, 2010). In recent years, many behavioral and functional neuroimaging studies suggest that long-term intensive bilingual experience boosts cognitive control (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Dong & Li, 2019; Prior & MacWhinney, 2010) and even short-term language switching training could tune the neural activity of cognitive control areas (Kang et al., 2017). However, in the rs-fMRI study by Sun et al. (2019), the high proficiency bilinguals were associated with weaker resting-state functional connectivity (rsFC) for the switching component of cognitive control. It is possible that as L2 proficiency increases, the intrinsic brain fluctuations of regions in salience network grow with the decrease of regional connectivity for cognitive control. Finally, ALFF of bilateral fusiform gyri correlated with L2 proficiency as brain activation of the same regions, which reinforced the contribution of fusiform gyrus in L2 learning of Chinese native speakers.

For task-based fMRI data, not surprisingly, we found that L2 proficiency was positively and significantly correlated with brain activation in language control areas, including the left SMA, bilateral insula, and right putamen. Specifically, the left SMA subserves speech articulation, helping bilinguals to access L2 phonology; the right parietal lobule is responsible for biasing selection towards the language in use; the basal ganglia including the putamen and caudate is sensitive to language switching (e.g., Abutalebi et al., 2013; Abutalebi & Green, 2008). For our late Chinese-English bilinguals, L2 proficiency is associated with increased brain activation in cognitive control areas during L2 processing. Grant, Fang, and Li (2015) reported that as L2 knowledge further improves, the connectivity between cognitive control and semantic areas may increase, and semantic access becomes automatic. Based on our findings and previous work, we hypothesize that with L2 proficiency increase, bilinguals' salience network is more active to coordinate different networks: the connections within the control network are weakened (Sun et al., 2019), and the connections between control network and semantic network are strengthened (Grant et al., 2015).

Finally, consistent with the results of the resting-state data, right fusiform gyrus showed greater neural responses in our Chinese-English bilinguals with higher L2 proficiency level. As mentioned above, late bilinguals might rely heavily on L1 semantic translation and actively engage visual orthographic analysis, which is associated with the fusiform gyrus. Our study, therefore, suggests that activity in right fusiform is a functional biomarker for L2 proficiency level in Chinese native speakers: right fusiform is not only crucial for L1 processing in Chinese speakers, but also vital for their learning of a new language in adulthood.

#### 4.2. Structural brain changes associated with L2 proficiency

L2 proficiency is associated with increased GMV in an extensive cortex-cerebellum network, including the SFG, MFG, IFG, fusiform

gyrus, and cerebellum, providing anatomical evidence for their functional neuroplasticity (see Li et al., 2014 for review). First, L2 learning performance is associated with auditory perception ability (Qi et al., 2019; Yang & Li, 2019). Thus, left STG and right MTG responsible for auditory processing showed a positive correlation with L2 proficiency. Second, L2 learning is constrained by L1 as L2 processing in late bilinguals needs to access L1 translation in late bilinguals. Again, we find L2 proficiency-related brain structural adaptation in bilateral fusiform gyri, which highlights its role in Chinese speakers' L2 learning. Finally, during L2 learning, the L1 network accommodates and assimilates L2 so that bilinguals can read in two languages (e.g., Perfetti et al., 2007). The angular gyrus has been consistently reported to be responsible for grapheme-to-phoneme mapping, an essential skill for alphabetic reading (e.g., Horwitz, Rumsey, & Donohue, 1998). Our Chinese-English bilinguals with increased L2 proficiency had larger gray matter volume in this area, suggesting that their L2 neural correlates become closer to native speakers. The precuneus in the present study seems to subserve memory-related imagery as a compensatory strategy for late bilinguals, coupling with the involvement of fusiform gyrus (e.g., Fletcher et al., 1995; Hebscher, Meltzer, & Gilboa, 2019). In sum, structural anatomical changes associated with L2 proficiency provide confirmatory evidence of the functional changes discussed above.

#### 4.3. Linking functional and structural neuroplasticity with L2 proficiency: fusiform gyrus

One key brain region that emerged from both our structural and functional imaging data is the right fusiform gyrus, which is correlated with L2 proficiency across three modalities of MRI measures, task-based fMRI, rs-fMRI, and sMRI. As discussed in the Introduction, the fusiform gyrus is a significant hub for orthographic processing. Chinese native speakers or learners of Chinese displayed more bilateral involvement of fusiform gyrus compared with the left-lateralized functional asymmetry in the same area associated with language processing in alphabetic language speakers. The bilateral engagement of right fusiform gyrus might be a result of long-term visuo-orthographic processing of Chinese characters with enormous amount training in handwriting (Cao et al., 2013).

Our findings are consistent with a recent fMRI study on Chinese-English bilinguals reading L1 and L2 words (Qu et al., 2019). They found that L2 proficiency modulates the cross-language pattern similarity in the bilateral fusiform cortex. However, in their study, increased L2 proficiency leads to greater pattern similarity in the left fusiform gyrus, but not in the right homolog; they argued that the right fusiform gyrus is related to non-linguistic processing. We suggest that low-proficient and intermediate-proficient Chinese-English bilinguals rely on L1 activation (phonology, orthography, and semantics) to access L2, which reflects the assimilation of L2 into the L1 system and engages right fusiform gyrus more than in L1. For highly-proficient Chinese-English bilinguals, their L2 can access the semantic system directly without much demand on L1 translation, and the corresponding neural substrates for language processing accommodate the features of L2, such as English, which requires more left-lateralized engagement of fusiform gyrus. This hypothesis is also consistent with Cao et al. (2019) who reported English native speakers recruited phonological regions in handwriting learning, while highly skilled Chinese native speakers recruited right fusiform gyrus in handwriting learning. Their results are based on that the English language is a phonological language that recruits more phonological areas, while Chinese language is a logographic language, which needs more non-linguistic visual-orthographic analysis associated with the right fusiform gyrus. Our finding that fusiform gyrus is implicated in both functional and structural data as a neural correlate of L2 proficiency in nonproficient Chinese-English bilinguals highlights the characteristics of L1 in tracing L2 learning-related neural changes, especially in low-to-high intermediately proficient Chinese-English bilinguals.

The present study has three limitations that should be addressed in the future. First, our bilinguals were late adult learners with low-to-high intermediate proficiency in L2. Therefore our conclusion is limited to this population and cannot be generalized to highly proficient Chinese-English bilinguals. Further studies could examine functional and structural neuroplasticity with L2 proficiency in advanced learners. Secondly, language experience, such as language exposure, immersion experience, and language switching frequency, are independent variables that define different bilingual populations thus should be studied as factors of interest in future explorations (DeLuca et al., 2019; see Li & Dong, 2020 for a recent review of these issues). Finally, the specific functions of anterior, middle and posterior fusiform gyri in Chinese speakers' language learning should be further examined, and the potentially fine-grained division of labor between the sub-areas should be studied with regard to the functional and structural brain changes in Chinese-English bilinguals of different L2 proficiency.

## 5. . Conclusions

Our study examined functional and structural neuroplasticity associated with L2 proficiency in Chinese-English late bilinguals. Several important findings from our study include: (1) L2 proficiency is associated with greater engagement of salient network in resting-state; (2) bilinguals with higher L2 proficiency recruit more neurocognitive resources for cognitive control; and (3) functional brain changes are consistent with structural neuroplasticity induced by L2 learning, especially with regard to the role of right fusiform gyrus as an important indicator of Chinese-English speakers' L2 learning success. These findings have significant implications for understanding the neural correlates of language proficiency and cognitive control in L2 learning and bilingual processing.

## Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## CRediT authorship contribution statement

**Ruiming Wang:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision. **Shuangshuang Ke:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Qi Zhang:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Ke Zhou:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. **Ping Li:** Writing - original draft, Writing - review & editing, Funding acquisition. **Jing Yang:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

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