Journal of Neurolinguistics 49 (2019) 202–213

Contents lists available at ScienceDirect

Journal of Neurolinguistics

journal homepage: www.elsevier.com/locate/jneuroling

Chinese phonological consistency effect in native and second language learners of Chinese: An fMRI study

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ARTICLE INFO

Keywords:
Consistency effect
Second language learning
Chinese character naming
Accommodation/assimilation hypothesis
Phonological processing

ABSTRACT

The neural basis of learning print-to-sound mapping when Chinese is the second language is still unclear. The present study aimed to examine the neural basis of the phonological consistency effect in non-native speakers who studied Chinese as a second language (L2 learners) for at least 1 year. The fMRI results indicated that the consistency effect occurred in the left supplementary motor area and left precentral gyrus in L2 learners, but not in native Chinese speakers, suggesting that L2 learners may utilize phonological-related regions and the motor system to facilitate inconsistent character processing. These results indicated that L2 learners used assimilation for the phonological processing of Chinese characters.

1. Introduction

In alphabetic languages, there are two main theoretical approaches that describe the representation of spelling-sound knowledge. According to the traditional dual-route model, spelling-sound knowledge is represented by a set of graphene-phoneme correspondence rules (GPC rules), such that a regular word follows the GPC rules while an irregular word does not (Baron & Strawson, 1976; Coltheart & Rastle, 1994; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). For example, "tooth" is a regular word, but "took" is an irregular word. Regular word reading is faster than irregular word reading, which is known as the regularity effect (Baron & Strawson, 1976; Content, 1991; Stanovich & Bauer, 1978). The connectionist model proposed that spelling-sound knowledge is represented by the weight of the connections between the spelling units and sound units. Because those units and connections are used for all words, the naming of a given word is influenced by the pronunciations of other similarly spelled words (Glushko, 1979; Seidenberg & McClelland, 1989; Sperling, Lu, Manis, & Seidenberg, 2005; Taraban & McClelland, 1987). Thus, the consistent words (e.g., WADE) are those with a word body (e.g., ADE) that is always pronounced identically whenever it appears in any word (e.g., LADE and HADE). Inconsistent words (e.g., HAVE) are those with a word body (e.g., AVE) whose pronunciation varies in different words (e.g., WAVE) (Glushko, 1979; Jared, 2002; Jared, McRae, & Seidenberg, 1990). Naming inconsistent words induces longer latency than naming consistent words (Jared, 1997, 2002; Jared et al., 1990), which is called the consistency effect. The consistency effect has been found in both high frequency words and low frequency words when the inconsistent words have the low frequency "friend" and the high frequency "enemy" (Jared, 1997). However, many studies have found that the regularity has little impact on naming high frequency words (Andrews, 1982; Jared et al., 1990; Seidenberg, 1985a). Researchers also found that the regularity effect disappeared when the frequency of the "friend" and the "enemy" was matched between the regular words and the

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https://doi.org/10.1016/j.jneuroling.2018.07.005
Received 19 December 2017; Received in revised form 30 May 2018; Accepted 16 July 2018
Available online 21 July 2018

irregular words, showing that the regularity effect actually depended on the neighborhood characteristics of the words. The researcher proposed that spelling–sound consistency was a better description to represent spelling-sound knowledge (Jared, 2002).

As a logographic writing system, the Chinese writing system is morphosyllabic, in that a morpheme is directly mapped to a syllable. Thus, Chinese characters have a larger grain size of orthography than alphabetic written systems. In Chinese, 80%–90% of characters are phonograms with phonetic and semantic radicals (Shu, Anderson, & Wu, 2000). Chinese characters rely on phonetic radicals to provide clues for their pronunciations. Regularity for Chinese characters is defined as whether a character's pronunciation is identical to the pronunciation of the phonetic radical itself. However, only 37.5% of Chinese characters are regular characters, indicating that the pronunciation of most Chinese characters cannot be predicted by the phonetic radical. Similar to alphabetical languages, the regularity effect was also found in Chinese character naming (Hue, 1992; Lee, Tsai, Su, Tzeng, & Hung, 2005; Seidenberg, 1985b), and the regularity effect was only observed in low frequency characters (Hue, 1992; Lee et al., 2005). Consistency for Chinese characters is defined as whether a character's pronunciation is identical with that of other characters that contain the same phonetic radical, which together form an orthographic neighborhood (Fang, Horng, & Tzeng, 1986). For example, "摇" (yao2) is a consistent character with the same pronunciation as its orthographic neighbors, such as "瑶" (yao2), "谣" (yao2), "遥" (yao2) and so on. "胖" (pang4) is an inconsistent character whose pronunciation is different from its orthographic neighbors such as "伴" (ban4), "判" (pan4), "畔" (pan4) and so on. A consistency effect was also found in naming Chinese characters, in that naming latency of inconsistent characters was longer than that of consistent characters, for both adults (Lee et al., 2005) and children (Zhao, Li, & Bi, 2012a). The consistency effect observed in Chinese character naming suggested that the naming latency of a word was influenced by its neighbors that have the same phonetic radical. The consistency effect was observed in a comparison of naming consistent/regular and inconsistent/regular words for both high and low frequency conditions, suggesting that consistency plays an important role in Chinese character naming (Lee et al., 2005).

The neural basis of the consistency effect has been explored by functional magnetic resonance imaging (fMRI) in recent years. For alphabetic languages, inconsistent words induced a higher activation in the left inferior frontal gyrus (IFG), left anterior insula, medial frontal/anterior cingulate cortex, left middle temporal gyrus (MTG)/inferior temporal sulcus (ITS) and the left fusiform gyrus compared to consistent words (Bolger, Hornickel, Cone, Burman, & Booth, 2008a; Bolger, Minas, Burman, & Booth, 2008b; Frost et al., 2005; Graves, Desai, Humphries, Seidenberg, & Binder, 2010). The left IFG is considered to be the critical region for phonological processing (Cornelissen et al., 2009; Fiez, Balota, Raichle, & Petersen, 1999; Tan, Laird, Li, & Fox, 2005; Wheat, Cornelissen, Frost, & Hansen, 2010). The left fusiform is a part of the ventral visual pathway that plays the most important role in visual word form processing, as well as an interface between the visual word form processing and the phonological processing (Dehaene & Cohen, 2011; Price & Devlin, 2011). Hence, the increased activity induced by inconsistent words in the left IFG and the left fusiform gyrus is likely to support the orthographic-to-phonological mapping. The left MTG/ITS is involved in semantic processing (Binder, Desai, Graves, & Conant, 2009; Visser, Jefferies, Embleton, & Lambon Ralph, 2012). Based on computational models of reading, additional semantic information is helpful for accessing the correct phonological representation when the mapping between the spelling and sound of the word is atypical (Harm & Seidenberg, 2004; Plaut & Booth, 2000; Strain, Patterson, & Seidenberg, 1995). Accordingly, increased activity of the left MTG/ITS reflected the involvement of semantic processing in inconsistent word reading, aiding to address the correct phonological representation (Graves et al., 2010). Only two studies focused on the neural basis of the consistency effect in Chinese character naming, and they showed that, compared to consistent characters, inconsistent characters demonstrated greater activation in the left IFG, anterior cingulate gyri, left middle frontal gyrus (MFG), left supplementary motor area (SMA), left anterior insula in the frontal cortex, left superior and inferior parietal lobules, left supramarginal gyrus in the left temporoparietal cortex and the left cuneus, left lingual gyrus and right fusiform gyrus in the occipitotemporal cortex in a lenient statistic threshold (Lee, Huang, Kuo, Tsai, & Tzeng, 2010; Lee et al., 2004). These results suggest that a set of brain regions, including the left inferior frontal gyrus, left temporoparietal cortex and the left occipitotemporal cortex, are involved in the consistency effect for both Chinese reading and alphabetic language reading (Lee et al., 2004). Meanwhile, the left MFG and the right fusiform are only involved in the consistency effect in Chinese reading (Lee et al., 2010) but not in alphabetic language reading (Bolger, Hornickel, et al., 2008a; Frost et al., 2005; Graves et al., 2010). Although controversial (Szwed, Qiao, Jobert, Dehaene, & Cohen, 2014), the left MFG is considered to be the region that uniquely supports the mapping of Chinese character forms into their pronunciation (Tan et al., 2001, 2005). Previous studies indicated that the right vOT, such as the right fusiform/lingual gyrus, was specifically involved in Chinese reading for the holistic visual processing of Chinese characters (Bolger, Perfetti, & Schneider, 2005; Cao et al., 2013; Perfetti et al., 2007; Tan et al., 2005). The increased activity of the left MFG and right fusiform in inconsistent Chinese character processing may suggest extra visual and phonological analysis in the orthographic-to-phonological transformation of Chinese characters.

It has been interesting to understand how the brain supports a second language (L2) in bilinguals. Learning Chinese as a second language for native alphabetic language speakers (hereafter referred to as L2 learners) is considered to be very difficult because of the complex features of Chinese characters. Previous studies found that L2 learners recruited additional regions, such as the right occipitotemporal cortex and the left MFG, during Chinese reading compared with first language reading (Liu, Dunlap, Fiez, & Perfetti, 2007; Nelson, Liu, Fiez, & Perfetti, 2009). These two regions were thought to be specific to Chinese reading (Bolger et al., 2005; Tan et al., 2005). These results showed that the L2 learners need to recruited additional brain regions that specially support Chinese character processing. Deng, Chou, Ding, Peng, and Booth (2011) found that the left IFG, which is found to be involved in both Chinese and alphabetic language processing, was also involved in the phonological processing of Chinese characters in L2 learners (Deng et al., 2011). This result showed that L2 learners may also use brain regions involved in their native language to support Chinese reading. Researchers proposed the "accommodation/assimilation" hypothesis to explain how the brain adapts to a second language. Specifically, if the L2 learners use the brain network of their first language (L1) to support the L2 processing, they show the assimilation pattern; if the L2 learners recruit additional brain regions that can support the specific processing of the L2 written system, they show the accommodation pattern (Perfetti, Liu, Fiez, & Tan, 2006). According to this hypothesis, the L2 learners showed the accommodation pattern because they recruited additional regions, such as the left MFG and the right occipitotemporal cortex, during Chinese reading. These results indicate that the neural network of alphabetic languages may not be sufficient to support Chinese reading because of the complex visual form and special way of mapping the visual form to its pronunciation. In previous studies, the participants received very short-term training in Chinese reading in the laboratory (Deng et al., 2011; Liu et al., 2007). The bilateral lingual gyrus was found to be more activated at the end of four weeks' training than at the end of two weeks' training (Deng et al., 2011), suggesting that the learning time had an influence on the activation in some regions. To observe a more stable effect of neural underpinning on Chinese reading, a relatively long period of time dedicated to learning Chinese reading is necessary. A recent fMRI study explored the brain activation of orthographic to phonological transformation of Chinese characters, by regular effect, in alphabetic language speakers who learned Chinese for 1 or 2 years in China (Zhao et al., 2012b). Ventral aspects of the left IFG and the left inferior parietal lobule (IPL) were found to be active for phonological processing of Chinese characters, and the right occipitotemporal cortex was active for orthographic processing in L2 learners. The authors suggested that L2 learners used the region specific to alphabetic languages for phonological processing of Chinese characters, while they used the regions specific to Chinese for orthographic processing of Chinese characters (Zhao et al., 2012b). However, in Zhao et al. (2012b), the comparison was based on visual inspection instead of statistically comparing the activation between L2 learners and Chinese native speakers.

The consistency effect was also found in L2 learners in that the naming accuracy of consistent characters was significantly higher than that of inconsistent characters (Lin & Collins, 2012). In this study, we aimed to explore the brain mechanisms underlying orthographic to phonological transformation via comparing the consistency effect between L2 learners and native Chinese speakers during character naming. We focused on the consistency effect to reveal the orthographic to phonological transformation for two reasons. First, the consistency effect is an important notion that describes the orthographic to phonological transformation, which is independent of regularity. Second, we used only high-frequency characters to ensure that L2 learners could recognize all of the characters. In previous studies, the regularity effect was found only in low-frequency characters (Hue, 1992; Lee et al., 2005), but the consistency effect was observed in both high and low-frequency characters (Lee et al., 2005). In the present study, L2 learners studied Chinese as a second language for more than 1 year in China, and their native languages were all alphabetic languages, such as Indonesian and English, which was reported in Zhao et al. (2012b). Moreover, we statistically compared brain activation between L2 learners and Chinese native speakers. Based on a previous study (Zhao et al., 2012b), we predicted that the left IFG (BA44) would be involved in the consistency effect in L2 learners, indicating that L2 learners use an assimilation pattern for phonological processing of Chinese characters. We also predicted that the right occipital cortex would be involved in orthographic processing of Chinese characters in L2 learners, indicating that L2 learners use an accommodation pattern for orthographic processing of Chinese characters.

2. Methods

2.1. Participants

The participants included 15 native Chinese speakers (mean age = 22.5 years, ranging from 19 to 25 years) and 15 alphabetic language speakers (L2 learners, mean age = 23 years, ranging from 19 to 30 years) whose native languages were English or Indonesian. The L2 learners were international students and had studied Chinese in China for more than 1 year. They all learned Chinese at the Beijing Language and Culture University and passed the HSK (Hanyu Shuiping Kaoshi) band three, which means that they mastered at least the 600 most commonly used Chinese characters. All participants were right-handed and had normal or corrected-to-normal vision. The data of two native Chinese speakers were excluded for excessive head motion. The movement exclusion criteria was larger than 3 mm or 3° in any direction. Thus, the fMRI data for 13 native Chinese speakers and 15 L2 speakers were analyzed. This experiment was approved by the ethics committee of the Beijing Normal University, and written consent was obtained from each participant prior to the experiment.

2.2. Stimuli and procedure

A mixed 2 × 2 factorial design was used, with consistency (consistent characters, inconsistent characters) as a within-subject factor and participant type (native Chinese speakers, L2 learners) as a between-subject factor.

To select proper stimuli, twenty L2 learners (fifteen of them took part in the fMRI experiment) participated in a pilot behavioral test. The participants were asked to loudly read the Chinese characters selected from the vocabulary self-testing handbook of Hanyu Shuiping Kaoshi (HSK). The correctly named characters (a total of 36 Chinese characters) were selected as stimuli for the following fMRI experiment. The characters consisted equally of two types: consistent characters and inconsistent characters. Phonological consistency (c) was calculated as the number of characters (n) sharing an identical pronunciation within an orthographic neighborhood with the same phonetic radical divided by the whole orthographic neighborhood size (N), $c = n/N$ (Fang et al., 1986). If the phonological consistency was higher than 0.5, the character was identified as a stimulus with a high level of phonological consistency. Inconsistent characters had a phonological consistency lower than 0.5. All characters had a left-right structure, and all characters had different phonetic radicals. The character frequencies were calculated according to the Modern Chinese Frequency Dictionary (Wang, Chang, & Li, 1985). The character frequencies, number of strokes, and number of homophones were matched between consistent characters and inconsistent characters, as shown in Table 1. All stimuli were presented using a block design. A

Table 1
Stimulus characteristics.

	Consistent characters		Inconsistent characters		Comparison	
	M	*SD*	*M*	*SD*	*t*	*p*
Character frequency	231.70	288.17	263.43	374.36	−0.28	0.77
Number of strokes	8.67	2.32	9.11	2.51	−0.55	0.58
Number of homophones	13.44	10.31	18.77	13.64	−1.32	0.19

Note. Character frequency values are occurrences per million.

character was visually presented for 1500 ms following a 500 ms blank within a trial. There were 18 trials within each task block that were then followed by a fixation block lasting 36 s as a baseline block. All participants underwent 2 repetitive runs. In each run, 4 task blocks (regular-consistent characters, regular-inconsistent characters, irregular-consistent characters and irregular-inconsistent characters) and 4 baseline blocks were alternately presented, lasting 4 min 48 s. To control for the regularity effect, we only used the trials of the regular-consistent characters condition and the regular-inconsistent characters condition from the two runs. During scanning, participants were asked to name the characters covertly in the task blocks and did not make any response in the baseline blocks.

2.3. Data acquisition

A 3.0-T Siemens scanner (Siemens Healthcare, Erlangen, Germany) was used to acquire functional and structural data. Functional data were collected with a gradient echo planar image (EPI) sequence sensitive to blood oxygen level dependent (BOLD) contrast. The scan parameters used were as follows: TR = 2000 ms, TE = 30 ms, flip angle = 90°, matrix size = 64 × 64, FOV = 20 cm, slice thickness = 4 mm, gap = 0.8 mm, and number of slices = 30. T1-weighted images were acquired for structural data and were used for anatomical reference. The scan parameters of the T1 images were as follows: TR = 250 ms, TE = 2.46 ms, flip angle = 70°, matrix size = 256 × 256, FOV = 20 cm, slice thickness = 4 mm, gap = 0.8 mm, and number of slices = 30.

2.4. Data analysis

Functional MRI data preprocessing was performed with Data Processing Assistant for Resting-State fMRI (DPARSF) (Yan, 2010). After slice acquisition time correction and head motion correction, the images were normalized to the Montreal Neurological Institute average template and interpolated to 3 × 3 × 3 mm cubic voxels. The data were spatially smoothed by a 6-mm FWHM Gaussian kernel.

Statistical Parametric Mapping-8 (SPM8, Wellcome Trust Centre for Neuroimaging, London, UK. http://www.fil.ion.ucl.ac.uk/spm) was used for a two-stage mixed effects model. In the first level of analysis, a hemodynamic response function (HRF) was produced by general linear modeling (GLM) for each experimental condition and each participant. In the second level of analysis, a two-way ANOVA, with within-subject factor conditions (consistent characters and inconsistent characters) and between-subject factor conditions (Chinese speakers and L2 learners), was conducted to explore the between-group differences in the consistency effect. The statistical threshold for all whole brain analyses was set at $p < 0.001$ voxel-wise and $p < 0.05$ cluster-wise using the Alphasim correction for multiple comparison correction. The Alphasim correction was performed by Rest toolbox (http://www.restfmri.net). Beta value extraction was conducted by the MarsBar toolbox in SPM 8 software (Brett, Anton, Valabregue, & Poline, 2002). Functional activation maps were displayed using the MRIcron toolbox (Rorden, Karnath, & Bonilha, 2007).

Table 2
Behavior results.

	Consistent characters		Inconsistent characters	
	M	*SD*	*M*	*SD*
Accuracy				
Native Chinese speakers	0.99	0.019	0.97	0.035
L2 learners	0.95	0.077	0.91	0.135
RT				
Native Chinese speakers	589.74	69.609	602.94	75.093
L2 learners	541.31	33.590	558.79	42.292

Table 3
Brain activations of task compared with baseline in the two experimental groups.

Brain region	Chinese speakers				L2 learners			
	t	Cluster size	BA	MNI coordinate	*t*	Cluster size	BA	MNI coordinates
Inferior occipital gyrus R	11.4	568	18	27, −90, 0	9.57	1426	19	42, −81, −8
Cerebellum Crus I R	7.12		19	39, −75, 20	–			
Inferior occipital gyrus R	6.84		19	39, −81, −4	–			
Angular gyrus R	–				9.4		7	30, −57, 52
Inferior temporal gyrus R	–				9.38		37	48, −66, −8
Middle occipital gyrus L	11.21	761	18	−27, −93, 0	–			
Lingual gyrus L	9.45		18	−36, −90, −12	11.62	933	18	−27, −93, −12
Inferior occipital gyrus L	8.39		19	−45, −75, −16	11.46		19	−45, −66, −12
Inferior parietal lobule L	5.56	68	7	−33, −57, 56	–			
Superior parietal lobule L	4.42		7	−24, −63, 52	–			
Supplementory motor area L	5.47	59	–	0, 0, 68	10.15	297	32	−3, 12, 52
Precentral gyrus L	–				14.07	906	44	−48, 6, 32
Insula L	–				7.15		48	−30, 21, 4
Precentral gyrus L	–				6.73		6	−33, 0, 64
Precentral gyrus R	–				6.94	277	44	48, 9, 32
Inferior frontal opercularis R	–				5.86		44	54, 21, 36
Inferior frontal triangularis R	–				5.61		45	54, 33, 20

Note. L, left; R, right. X, y, z are MNI coordinates.

3. Results

3.1. Behavior results

Accuracy and reaction time (RT) were recorded (Table 2). Accuracy was analyzed in a 2 (group: native Chinese speakers, L2 learners) × 2 (phonological consistency: consistent characters, inconsistent characters) repeated-measure ANOVA. The main effect of consistency was significant [$F(1, 28) = 6.973$, $p < 0.05$, $\eta^2 = 0.199$]; the accuracy of consistent characters was higher than that of inconsistent characters. The main effect of group was not significant [$F(1, 28) = 2.661$, $p = 0.114$, $\eta^2 = 0.087$]. The interaction effect between group and consistency was not significant [$F(1, 28) = 0.981$, $p = 0.331$, $\eta^2 = 0.034$]. The trials with wrong reactions or exceeding 3 SD of average RTs were excluded. The RT was analyzed in a 2 (group: native Chinese speakers, L2 learners) × 2 (phonological consistency: consistent characters, inconsistent characters) repeated-measure ANOVA. The main effect of consistency was significant [$F(1, 28) = 7.883$, $p < 0.01$, $\eta^2 = 0.22$]; the RT of consistent characters was shorter than that of inconsistent characters. The main effect of group was significant [$F(1, 28) = 5.141$, $p < 0.05$, $\eta^2 = 0.155$]; the RT of the L2 learners was shorter than that of the native Chinese speakers. The interaction effect between group and consistency was also not significant [$F(1, 28) = 0.153$, $p = 0.698$, $\eta^2 = 0.005$]. These results showed that there was a phonological consistency effect in both native Chinese speakers and L2 learners.

3.2. fMRI results

Compared to the baseline, Chinese character naming activated the left MOG, left IPL, left SMA and right inferior occipital gyrus (IOG) in Chinese speakers. In L2 learners, naming Chinese characters activated the bilateral precentral gyrus, left lingual gyrus, left

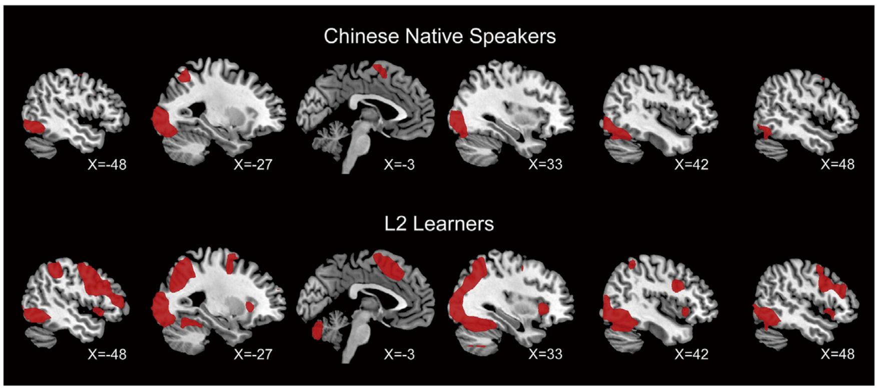

Fig. 1. Brain Activation of the Task Compared with the Baseline in the Two Groups. The upper row shows the brain activity of the Chinese speakers, while the lower row shows the brain activity of the L2 learners.

Table 4
Brain activations of consistent and inconsistent characters with baseline in the two experimental groups.

Brain region	Chinese speakers				L2 learners			
	t	Cluster size	BA	MNI coordinate	*t*	Cluster size	BA	MNI coordinates
Consistent characters					–			
Inferior occipital gyrus L	–				5.65	579	19	−45, −66, −12
Fusiform gyrus L	–				5.37		37	−39, −51, −16
Middle occipital gyrus L	6.48	485	18	−27, −90, 0	5.32		17	−24, −96, 8
Cerebellum Crus I L	6.16		19	−39, −66, −24	–			
Lingual gyrus L	5.9		18	−36, −90, −12	–			
Cerebellum 6 R	–				6.88	868	19	30, −66, −20
Inferior temporal gyrus R	–				6.42		37	45, −60, −8
Inferior occipital gyrus R	6.44	271	18	27, −90, 0	5.95		19	42, −81, −4
	5.59		19	39, −81, −4	–			
Inferior temporal gyrus R	4.5		37	45, −60, −12	–			
Supplementary motor area L	4.39	70	6	−3, 9, 56	5.51	105	32	−6, 15, 48
	3.93		6	−3, −3, 68	5.34		6	−3, 9, 56
Supplementary motor area R	3.92		6	6, 0, 68	–			
Medial superior frontal gyrus L	–				4.03		32	−6, 24, 40
Inferior parietal lobule L	–				4.97	277	40	−42, −39, 44
Superior parietal lobule L	3.96	38	7	−30, −57, 56	4.87		7	−24, −66, 48
					4.8		7	−33, −60, 52
Precentral gyrus L	–				7.52	236	44	−48, 6, 32
	–				4.65		6	−51, 6, 48
	–				3.5		6	−45, −3, 56
Cerebellum 8 R	–				5.37	131	–	18, −69, −44
Cerebellum Crus II R	–				5.14		–	9, −78, −36
	–				4.92		–	6, −72, −28
Insula L	–				4.82	65	48	−30, 21, 4
	–				3.75		–	−42, 18, −4
	–				3.65		48	−42, 9, 0
Insula R	–				3.46	46	48	
Inconsistent characters	–				–			
Inferior temporal gyrus R	–				8.33	654	37	48, −60, −12
	–				8.3		19	42, −81, −8
Inferior occipital gyrus R	9.09	433	18	27, −90, 0	8.1		19	30, −87, −8
	5.05		19	30, −81, −12	–			
Cerebellum Crus II R	–				6.5	173	–	6, −78, −28
Cerebellum 8 R	–				6.41		–	24, −69, −48
Cerebellum Crus I R	6.29		19	39, −75, −20	5.4		18	9, −81, −20
Superior parietal lobule L	–				9.27	491	7	−24, −66, 48
Superior parietal lobule L	–				8.66		7	−30, −60, 52
Middle occipital gyrus L	8.89	557	18	−27, −93, 0	7.03		19	−27, −69, 32
Calcarine L	8.37		18	−12, −99, −8	–			
Lingual gyrus L	7.15		18	−36, −90, −12	11.43	795	18	−27, −93, −12
Inferior occipital gyrus L	–				10.16		19	−45, −66, −12
Precentral gyrus L	–				13.02	642	44	−48, 6, 32
Precentral gyrus L	–				7.29		6	−33, 0, 64
Precentral gyrus L	–				6.49		6	−45, 3, 56
Supplementary motor area L	–				10.07	261	–	0, 9, 56
Angular gyrus R	–				8.12	218	7	30, −57, 52
Middle occipital gyrus R	–				7.39		19	30, −69, 32
Inferior frontal opercularis R	–				6.58	288	44	54, 15, 32
Inferior frontal opercularis R	–				6.47		44	48, 9, 28
Inferior frontal triangularis R	–				6.26		45	54, 33, 20
Insula L	–				5.82	79	48	−30, 21, 4
Orbital frontal inferior gyrus L	–				4.03		47	−42, 18, −8

Note. L, left; R, right. X, y, z are MNI coordinates.

SMA, right IOG and right insula (Table 3 and Fig. 1).

In Chinese speakers, naming consistent characters activated the left MOG, left lingual gyrus, left SPL, left IPL, left SMA, right IPL and right inferior temporal gyrus (ITG). Naming inconsistent characters activated the left MOG, left calcarine, left lingual gyrus, left IPL and right inferior occipital gyrus (IOG). In L2 learners, naming consistent characters activated the left IOG, left MOG, left fusiform gyrus, left IPL, left SPL, left SMA, left precentral gyrus, left medial superior frontal gyrus (SFG), left insula, right ITG, right IOG and right insula. Naming inconsistent characters activated the left IOG, left MOG, left lingual gyrus, left SPL, left SMA, left precentral gyrus, left insula, right IOG, right MOG, right ITG, right angular gyrus and right inferior frontal gyrus (Table 4).

We computed the differences in brain activation between inconsistent characters and consistent characters as the consistency effect. As shown in Fig. 2 and Table 5, the consistency effect was found in the left calcarine ($d = 0.8$), and right lingual gyrus ($d =$

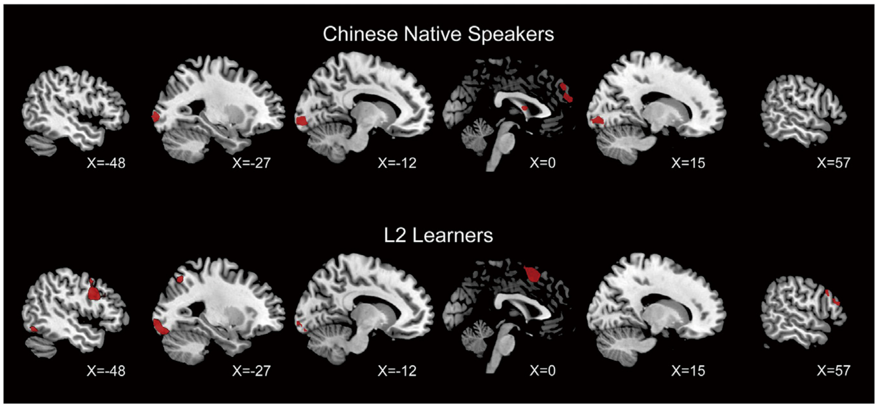

Fig. 2. Consistency Effect in the two Groups. The upper row shows the brain activity of Chinese speakers, while the lower row shows the brain activity of L2 learners.

Table 5
Consistency effect in the two experimental groups.

Brain region	Chinese speakers				L2 learners			
	t	Cluster size	BA	MNI coordinates	*t*	Cluster size	BA	MNI coordinates
Calcarine L	5.65	69	18	−12, −99, −8				
Lingual gyrus R	3.99	38	18	15, −87, −4				
Middle occipital gyrus R	3.9		18	27, −90, 4				
Lingual gyrus L	–				5.98	168	18	−27, −93, −12
Fusiform gyrus L	–				4.74		19	−45, −63, −16
Lingual gyrus L	–				4.45		18	−36, −90, −12
Precentral gyrus L	–				5.88	128	44	−48, 6, 32
Inferior frontal triangularis L	–				3.41		45	−51, 30, 24
Inferior frontal triangularis L	–				3.37		44	−51, 24, 32
Supplementary motor area L	–				5.58	57	6	0, 9, 56
Inferior frontal triangularis R	–				4.23	49	45	57, 33, 20
Inferior frontal opercularis R	–				4		–	54, 18, 40
Inferior frontal triangularis R	–				3.86		48	48, 24, 24

Note. L, left; R, right. X, y, z are MNI coordinates.

1.25) extended to the right middle occipital gyrus ($d = 1.32$) in Chinese speakers. In L2 learners, the consistency effect was found in the left precentral gyrus ($d = 1.81$) extended to left pars triangularis of the inferior frontal gyrus ($d = 0.71$), left lingual gyrus ($d = 4.04$), left fusiform gyrus ($d = 1.7$), left supplementary motor area ($d = 2.35$) and right pars triangularis of the inferior frontal gyrus ($d = 1.32$).

An interaction effect between consistency and group was only found in the left SMA ($d = 0.81$) at the present threshold. We also found an interaction effect in the left precentral gyrus ($d = 0.58$) in which activation was extended to the left pars triangularis of the inferior frontal gyrus, right lingual gyrus ($d = 0.66$), left medial frontal gyrus ($d = 0.44$), and right superior parietal lobule (SPL) ($d = 0.45$) at a lenient threshold of $p < .005$, uncorrected (Table 6). The beta value was obtained from regions showing the interaction effect separately for each consistency condition (consistent characters and inconsistent characters) and each group of participants. In the left SMA, post-hoc Bonferroni tests showed that the consistency effect was detected in the activation of the left SMA ($p < 0.001$), the left precentral gyrus ($p < 0.05$) and the left medial frontal gyrus ($p < 0.01$) in L2 learners but not in Chinese native speakers (see Fig. 3). In the right lingual gyrus, post-hoc Bonferroni tests showed that the activation from inconsistent characters was

Table 6
Brain activations of the interaction effect between consistency and group.

Brain regions	*F*	Cluster size	BA	MNI coordinates
Supplementary motor area L	20.47	50	6	0, 12, 56
Precentral gyrus L*	15.78	33	44	−48, 6, 32
Lingual gyrus R*	13.86	13	18	18, −81, −4
Medial superior frontal gyrus L*	13.01	75	10	−6, 57, 4
Superior parietal lobule R*	12.65	14	7	18, −63, 52

Note. L, left; R, right. X, y, z are MNI coordinates. * Activations were significant at voxel-wise $p < 0.005$ uncorrected.

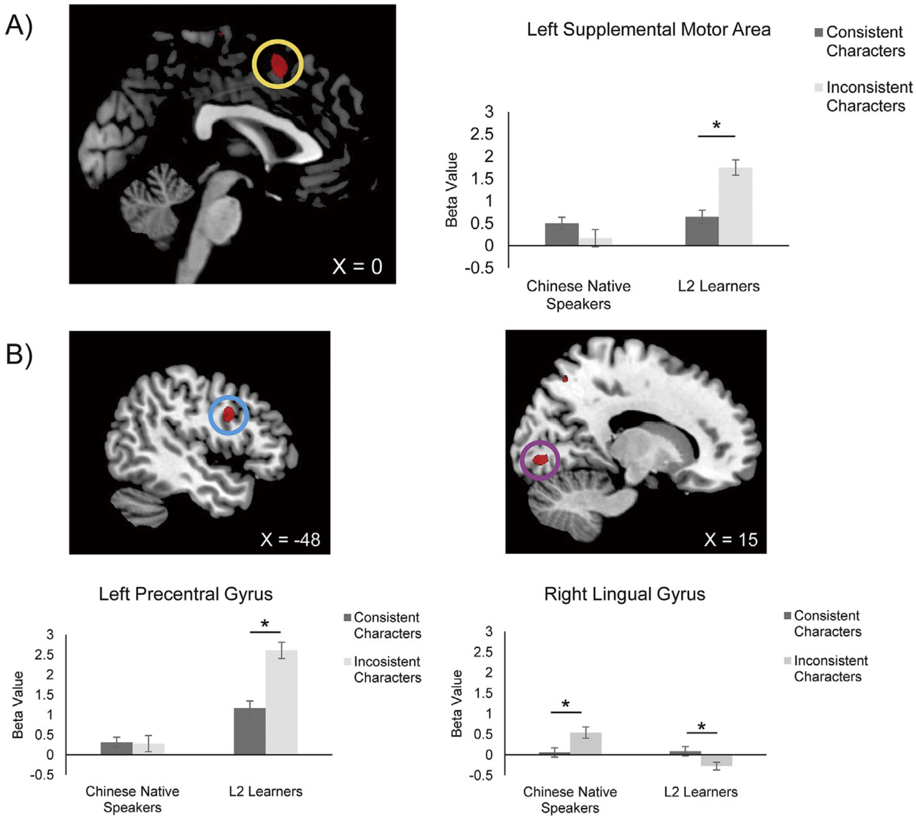

Fig. 3. Interaction Effect between Consistency and Group. A) Left supplementary motor area showing the interaction effect between the consistency and group at a statistical threshold of $p < .001$, Alphasim corrected. B) Left precentral gyrus and right lingual gyrus showing the interaction effect between the consistency and group at the statistical threshold of $p < .005$, uncorrected. Bar graphs represent the mean beta values of each cluster, and error bars represent SEM. *, $p < .05$.

significantly higher than that from consistent characters in Chinese native speakers ($p < 0.01$), and in the right superior parietal lobule, post-hoc Bonferroni tests showed that the activation from inconsistent characters was significantly greater than that from consistent characters in Chinese native speakers ($p < 0.05$) but not in L2 learners ($p = 0.204$).

4. Discussion

In the present study, two main results were found. First, a consistency effect was found in the left calcarine, right lingual gyrus and right MOG in native Chinese speakers. In L2 learners, a consistency effect was found in the left precentral gyrus, bilateral pars triangularis of the IFG, left lingual gyrus and left SMA. Second, the results of the interaction effect between consistency and group also showed that the consistency effect was found in the left SMA in L2 learners but not in native Chinese speakers.

The right lingual gyrus and right MOG are involved in orthographic processing, especially in Chinese character processing compared to alphabetic language processing (Bolger et al., 2005; Cao et al., 2013; Deng et al., 2011; Tan et al., 2005). In the present study, a consistency effect was found in the right lingual gyrus and right MOG in native Chinese speakers, which means that inconsistent characters induced more activity in these two brain regions than consistent characters did. Consistent characters have more neighbors with the same pronunciation within their orthographic neighborhood, which would facilitate accessing the phonological information of the target characters. However, inconsistent characters have more neighbors with different pronunciations within their orthographic neighborhood, which would interfere with accessing phonological information. A previous study provided evidence for those influences (Li, Bi, Wei, & Chen, 2011). In the study by Li et al. (2011), character naming was shown to be influenced by the pronunciation of characters within the same neighborhood. Researchers also suggested that Chinese reading may rely on orthographic processing more than phonological processing because there are many homophones in Chinese (Perfetti, Cao, & Booth, 2013). Thus, native Chinese speakers may utilize more orthographic processing to facilitate the recognition of inconsistent characters.

In L2 learners, we found that the left SMA, left IFG (BA44), and left precentral gyrus were involved in the consistency effect. In previous studies, the left IFG was found to be activated more when reading inconsistent words than when reading consistent words in alphabetic languages, which is identical to our results (Bolger, Hornickel, et al., 2008a; Bolger, Minas, et al., 2008b; Fiez et al., 1999; Frost et al., 2005; Graves et al., 2010). The left dorsal IFG (BA 44) is considered to be the critical region for phonological processing in alphabetic languages (Cornelissen et al., 2009; Fiez et al., 1999; Tan et al., 2005; Wheat et al., 2010). In our study, greater activation of the left IFG was found when reading the inconsistent characters than when reading the consistent characters, suggesting that reading inconsistent characters may require more effort to process phonological information than reading consistent characters for L2 learners. One study showed that the activation of the left IFG was related to task difficulty or task demand instead of phonological processing in Chinese reading (Yang, Wang, Shu, & Zevin, 2011). It is possible that the task of reading Chinese characters was more difficult for L2 learners than native Chinese speakers. However, we believe the activation in the left IFG in our results cannot solely be attributed to the task difficulty for several reasons. First, as mentioned before, the IFG (BA44), a part of Braca's area, has been consistently considered as the phonological processing region while reading in alphabetic languages (Fiez, 1997; Poldrack et al., 1999). Second, Yang et al. (2011) used a one-back task which the demand for working memory differs in different types of stimuli (Wang, Yang, Shu, & Zevin, 2011). In our study, we used the reading task. The behavior results showed that the main effect of group and the interaction effect between group and consistency were not significant in accuracy. Thus, we think that the task demand, such as the working memory, was not biased for any types of stimuli or participants in our study.

We found a difference in the left SMA in the group comparison for consistency effect. The SMA has been clearly divided into two distinct regions: the pre-SMA and SMA-proper (Picard & Strick, 1996). In language tasks, the pre-SMA is involved in high-level planning and guiding word pronunciation selection, while the SMA-proper is involved in actual motor speech execution (Alario, Chainay, Lehericy, & Cohen, 2006). The cluster in the left SMA in our results was clearly located in the pre-SMA. Compared with consistent characters, reading inconsistent characters may be greatly influenced by the differing phonological information of its neighbors, so the left pre-SMA may facilitate selecting the correct pronunciation of inconsistent characters for L2 learners. Moreover, the left precentral gyrus was found to be important for articulation of speech (Takayama, Sugishita, Kido, Ogawa, & Akiguchi, 1993). The functional connectivity between the left SMA and the left precentral gyrus was also found to be important for phonological rehearsal when learning words of a new language (Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010). Our results showed that the L2 learner may have utilized the motor system, including the left pre-SMA that is responsible for the selection of the correct pronunciation and the left precentral gyrus that is responsible for articulation, to facilitate naming inconsistent characters. In summary, our results indicate that L2 learners may require more effort to access the phonology of inconsistent characters through the utilization of the motor system.

We also found a consistency effect in the left lingual gyrus and the left fusiform gyrus in L2 learners. The left ventral occipito-temporal cortex, especially the left fusiform gyrus, is important for orthographic processing in both alphabetic languages and Chinese (Bolger et al., 2005; Cohen et al., 2000; Dehaene & Cohen, 2011; Price & Devlin, 2011). Researchers have noted that the left fusiform may serve as an interface between orthographical and phonological information (Price & Devlin, 2011). Top-down modulation from phonological processing regions, such as the left IFG, may increase the activity of the left fusiform (Mano et al., 2013; Price & Devlin, 2011; Twomey, Kawabata Duncan, Price, & Devlin, 2011). A previous study also found a consistency effect in the left fusiform gyrus in alphabetic languages, and the degree of activation in the left fusiform gyrus was correlated with reading ability (Bolger, Minas, et al., 2008b).

The “accommodation/assimilation” hypothesis has been used to interpret how the brain regions are involved in processing a second language in bilinguals (Nelson et al., 2009; Perfetti et al., 2007). In the present study, we found a consistency effect in the left IFG (BA44) and left SMA (BA 6) in L2 learners, suggesting that more phonological processing was needed when naming inconsistent Chinese characters than consistent Chinese characters. The left IFG (BA44) and left SMA (BA 6) are thought to play more important roles in the phonological processing of alphabetic languages compared to Chinese (Tan et al., 2005). Our results showed that L2 learners applied the brain regions associated with their native language to process phonological information of the second language, suggesting an assimilation pattern. Several studies have found that participants tend to use an assimilation strategy to process the phonological information of their second language (Cao et al., 2013; Deng et al., 2011; Stein et al., 2009; Zhao et al., 2012b). In particular, the observation that the native speakers of alphabetic languages use an assimilation strategy to process Chinese phonological information was also seen in a previous study (Deng et al., 2011; Zhao et al., 2012b). Chinese characters use an addressed phonology system, which maps orthographical information into phonological information at the syllable level. It was assumed that this addressed phonology system is supported by the left dorsal lateral frontal cortex (BA 9) (Tan et al., 2005). The left IFG (BA 44) and the left SMA (BA 6) were assumed to support the assembled phonology system of alphabetic languages, which maps them into fine-grained phonemic units (Tan et al., 2005). The question is, how do the L2 learners use brain regions supporting an assembled phonological system to process an addressed phonological system? Although there is no GPC rule in Chinese, the phonetic radicals still provide clues for the pronunciation of the character, which is the knowledge of the orthography–phonology relationship in Chinese. Studies have shown that knowledge of the orthography–phonology relationship plays an important role in leaning Chinese. This knowledge could help young children to learn new characters (Shu et al., 2000) and could also help non-native speakers of Chinese to learn Chinese characters (Shen & Ke, 2007). One possibility is that L2 learners use the brain regions supporting an assembled phonological system to process the knowledge of the orthography–phonology relationships in Chinese. Another possibility is that L2 learners may use the pinyin system to facilitate memorization of the pronunciation of Chinese characters. The pinyin system is an alphabetic system that represents the pronunciation of Chinese characters, which was developed in the early 1970s. The pinyin system is taught in schools all over China when students start to learn to read characters. People can use pinyin systems to facilitate remembering the pronunciation of Chinese characters and learning the pronunciation of a new character. Pinyin is also used to input Chinese characters into computer systems using alphabetic keyboards. A previous study showed that activation of the left IFG was also found in pinyin reading (Chen, Fu, Iversen, Smith, & Matthews, 2002). L2 learners may use the brain regions related to assembled phonology systems to facilitate the processing of the pinyin system when recalling the pronunciation of Chinese characters.

Several possible factors have been found to impact on the assimilation/accommodation pattern, such as the age of acquisition, L2 proficiency and the distance between L2 and L1 (Cao et al., 2013; Das, Padakannaya, Pugh, & Singh, 2011; Kim et al., 2016; Stein et al., 2009; Yokoyama et al., 2013). In the present study, the native languages of the L2 learners included English and Indonesian, and thus, the influence of the L2 learners' native language on the present results regarding the accommodation/assimilation pattern should be taken into account. However, English and Indonesian are both alphabetic languages that are made up of the Latin letters visually. Meanwhile, based on the orthography to phonology correspondences, English and Indonesian are both remarkably transparent languages compared with Chinese. The distance between English or Indonesian to Chinese should be similar. Thus, we believe that the differences between English and Indonesian, if any, would not substantially influence the results.

We did not find a consistency effect in the right lingual gyrus or the right MOG in L2 learners. However, most of the previous studies found that the right lingual gyrus or the right MOG were involved in Chinese character reading in L2 learners, which suggests that L2 learners utilize an accommodation pattern to process the orthographic information of Chinese characters (Liu et al., 2007; Nelson et al., 2009; Zhao et al., 2012b). In the present study, we found that both consistent and inconsistent characters induced activation of the right MOG in L2 learners. Thus, the right MOG may take part in processing both consistent and inconsistent characters. These results suggest that L2 learners must accommodate the Chinese-specific regions to process orthographic information of Chinese characters, which is actually consistent with previous studies.

Since some brain regions related to orthographic processing were activated in the current study, such as the left fusiform gyrus and left lingual gyrus, we calculated the orthographic neighborhood size for consistent characters and inconsistent characters. The mean orthographic neighborhood size was 8.44 (SD: 5.22) for consistent characters and 13.61 (SD: 5.64) for inconsistent characters. The orthographic neighborhood size of the inconsistent characters was significantly larger than that of the consistent characters [$t(34) = -2.849, p < 0.01$], suggesting that the orthographic neighborhood size may be a confounding factor in the present study. In the current study, greater activation was induced in the left fusiform gyrus and the left lingual gyrus by reading inconsistent characters than by reading consistent characters in L2 learners. In native Chinese speakers, greater activation of the right MOG was induced by reading inconsistent characters than by reading consistent characters. These results may also reflect the influence of the orthographic neighborhood size. Only one previous study has explored the neural basis of the orthographic neighborhood size effect in inconsistent character reading in native speakers (Li et al., 2011). Greater activation of the left middle frontal gyrus was induced by characters with a small orthographic neighborhood size compared to characters with a large orthographic neighborhood size (Li, Bi, & Zhang, 2010). However, in our results, the brain regions related to orthographic processing were activated more for inconsistent character reading compared to consistent character reading, corresponding to characters with a larger orthographic neighborhood size and characters with a smaller orthographic neighborhood size, respectively. In addition, in L2 learners, the activation induced by inconsistent character reading was greater than that induced by consistent character reading in the left precentral gyrus, left inferior frontal gyrus (BA 44), and left supplementary motor area (BA 6). Based on previous studies, these regions are considered to be critical for phonological processing in alphabetic languages (Alario et al., 2006; Cornelissen et al., 2009; Veroude et al., 2010; Wheat et al., 2010), which may reflect the phonological processing in reading in L2 learners. However, the orthographic neighborhood size effect is still an uncontrolled factor in the current study. It is very difficult to explain the interaction between the phonological consistency effect and the orthographic neighborhood size effect found in this study. Further studies are needed to explore the interaction between phonological consistency and the orthographic neighborhood size.

In the present study, in native Chinese speakers, the consistency effect was not found in the left frontal cortex, including the left IFG, left SMA and left MFG, which is inconsistent with the results of Lee et al. (2004) and Lee et al. (2010). We only used high-frequency characters to ensure that L2 learners could recognize all of the characters. In Lee et al. (2004) study, both high and low frequency characters were used, and, compared to low frequency characters, high frequency characters elicited a significantly lower activation in extensive brain areas, such as the left IFG, left SMA, and left MFG. Another study also reported that no regions in the left frontal cortex were significantly activated when naming high frequency Chinese characters (Peng et al., 2004). Importantly, the authors observed an interaction between frequency and consistency in native Chinese speakers. For the high frequency characters alone, no regions in the left frontal cortex were found to be associated with the consistency effect (Lee et al., 2004). There is also an alternative interpretation for the difference between our results and previous results, which is due to the different experimental design. In the studies of Lee et al. (2004) and Lee et al. (2010), the researchers used the event-related design, which mixed various types of stimuli in one run. However, the present experiment used the block design, which means a block only contained one stimuli type, and several block were contained in one run. Considering the relatively small sample in our study, we chose the block-design paradigm because it produced a higher signal-to-noise ratio than an event-related paradigm. One behavioral study indicated that the block design that was used in the present study may introduce a confounding of attentional control (Zevin & Balota, 2000) because the participants may rely more on a stimulus-specific processing approach in the block design than in the event-related design. The difference between the two conditions could also be attributed to the different allocation of the attention resource. This confounding cannot be ruled out in this study. However, this confounding may be controversial because the results Lee et al. (2004) obtained from their study using the ER design were similar to those found in our study. Another study compared the block and event-related fMRI designs in the word frequency effect. The study demonstrated that the brain regions activated in the block design were similar to those activated in the event-related design. However, the activation amplitude was lower in the event-related design than in the block design (Chee, Venkatraman, Westphal, & Siong, 2003). These results suggested that the fMRI experimental design may not have a significant influence on results.

5. Conclusion

We explored the neural basis of the consistency effect in L2 learners. We found that L2 learners used phonological regions and the motor system to facilitate inconsistent character naming. L2 learners displayed an assimilation pattern for phonological processing of Chinese characters and an accommodation pattern for orthographic processing of Chinese characters.

Acknowledgments

This research was supported by Grants from the National Natural Science Foundation of China (31371044, 31671155) and Beijing Advanced Innovation Center for Imaging Technology (BAICIT-2016018). The authors have no conflicts of interest.

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