Neural basis of phonological processing in second language reading: An fMRI study of Chinese regularity effect

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A B S T R A C T

The present study examined the neural basis of phonological processing in Chinese later acquired as a second language (L2). The regularity effect of Chinese was selected to elucidate the addressed phonological processing. We recruited a group of alphabetic language speakers who had been learning Chinese as L2 for at least one year, and a control group of native Chinese speakers. Participants from both groups exhibited a regularity effect in a pilot behavioral test. Neuroimaging results revealed that L2 learners exhibited stronger activation than native Chinese speakers in the right occipitotemporal region (i.e. right lingual gyrus and right fusiform gyrus). Moreover, L2 learners exhibited greater activations in the ventral aspects of the left inferior parietal lobule (LIP) and the left inferior frontal gyrus (LIFG) for irregular character reading minus regular character reading. In contrast, native Chinese speakers exhibited more dorsal activations in the LIP and LIFG. According to the "accommodation/assimilation" hypothesis of second language reading, the current findings suggest that native speakers of alphabetic languages utilized an accommodation pattern for the specific requirements of the visual form of Chinese characters, and an assimilation pattern for orthography-to-phonology transformation in Chinese reading.

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Introduction

The way in which a later learned language (i.e. the second language; L2) is organized in the brain relative to the first language (L1) is currently unclear. Several neuroimaging studies have explored the L2 mechanisms, reporting common brain areas which are involved in both L1 and L2 processing, including the left superior temporal gyrus (in a study of Spanish–English bilinguals by Marian et al., 2003), the bilateral occipital lobe (in a study of Korean–English bilinguals by Suh et al., 2007), and the left ventral occipitotemporal cortex (in a study of Spanish–English bilinguals by Leonard et al., 2010). In addition to these overlapping regions, additional activations have been reported in areas specific to L2 processing (Lehtonen et al., 2009; Leonard et al., 2010; Marian et al., 2003; Pillai et al., 2003; Suh et al., 2007; Yokoyama et al., 2006). Inconsistent findings regarding the common/distinct brain areas between L1 and L2 may be due to different task difficulties and processing stages. Marian et al. (2003) proposed that shared cortical structures might reflect the characteristics of early stages in language processing, while separate structures reflect the distinction between two languages at later stages of processing. Although this hypothesis can account for the above-mentioned results in alphabetic language systems (e.g. overlapping in occipitotemporal regions that are associated with the early processing such as visual and phonetic analysis), it cannot fully explain the findings across different types of writing systems (e.g. alphabetic vs. logographic). Nelson et al. (2009) found that English speakers who learned Chinese as L2 recruited activities in the left fusiform gyrus while viewing English words, but recruited activities in the right fusiform gyrus while viewing Chinese characters. This finding suggests that distinct activations between L1 and L2 also can be found at early stages of processing, such as visual form processing. Therefore, not only the stage of processing but also specific language characteristics appear to contribute to the distinctive activation patterns between L1 and L2, and different language systems would be expected to elicit very different requirements on lexical processing.

The "accommodation/assimilation" hypothesis (Perfetti and Liu, 2005) offers a general interpretation based on the neural substrate of bilingualism. According to this hypothesis, in the condition that native language network is sufficient for the processing demands of new languages, the L1 system can assimilate an L2 system by applying neural circuits already in place for the native language to process the later acquired one. However, if the original language network cannot support the specific processing demands of L2, it must accommodate the corresponding neural structures of the new language. In view of this hypothesis, Chinese–English bilinguals (with English as L2) should show an assimilation pattern when processing English, i.e. engaging similar regions as their native language. This notion...
has been supported by several studies, in which the right fusiform gyrus (subareas of the right occipitotemporal regions, OT regions) was involved in orthographic processing (Lee et al., 2004; Nelson et al., 2009; Tan et al., 2003) and the left middle frontal gyrus (LMFG) was specific for phonological processing (Tan et al., 2003, 2005). These two regions are thought to be specific for Chinese processing (Perfetti and Liu, 2005; Tan et al., 2005). On the other hand, when alphabetic language speakers (e.g. native English speakers) learned Chinese as L2, they would be expected to show an accommodation pattern, i.e. recruiting brain regions specific for Chinese, not for English. As mentioned above, some evidence indicated that English–Chinese bilinguals activated the right fusiform gyrus in response to the additional requirement of visual analysis when viewing Chinese characters (Nelson et al., 2009). Evidence from training studies has reported similar findings (Deng et al., 2008, 2011; Liu et al., 2007).

Considering that a major difference between alphabetic and logographic language systems (e.g. English vs. Chinese) is the way in which visual words map onto speech sounds (assembled vs. addressed), it is particularly important to test the accommodation/assimilation hypothesis on phonological processing between these two writing systems. A meta-analysis of neuroimaging studies on native language speakers has suggested a distinct network for Chinese phonological processing compared with alphabetic language systems (Tan et al., 2005). The LMFG and the dorsal aspect of the left inferior parietal lobule (L IPL) are thought to be regions more specific for phonological storage in Chinese, while the left inferior frontal gyrus (LIFG) and the ventral aspect of the IPL are thought to be key regions for assembled phonological processing (more strongly involved in alphabetic processing). Two recent studies explored the phonological learning effect in Chinese by employing a lexical training paradigm with native English speakers (Deng et al., 2011; Liu et al., 2007). Liu et al. (2007) found that L2 learners induced activation in the LMF G, the dorsal aspect of LIFG (Talairach coordinates [−44, 25, 18]), and the ventral aspect of IPL ( [−33, −54, 39]). Deng et al. (2011) also reported that the right occipital region and the left inferior frontal region exhibited greater involvement after learning Chinese. Thus, these two studies demonstrated both an accommodation pattern and an assimilation pattern when native English speakers learned to read Chinese. However, these studies were based on short-term training, more evidence is needed to examine the effects of assimilation/accommodation in phonological processing among naturally acquired English–Chinese bilinguals, and to compare L2 learners directly with native speakers. To our knowledge, no such studies have been reported.

The regularity effect is a commonly found effect in Chinese phonological processing (Yang and Shu, 2008; Zhang et al., 2003). Different from alphabetic languages, Chinese has no grapheme–phoneme correspondences (GPCs). Regularity in Chinese is defined by whether pronunciation of a compound is identical to that of its phonetic radical or not (e.g. Lee et al., 2005; Peng et al., 2004; Pollatsek et al., 2000; Tan et al., 2001a). When the phonetic radical is pronounced in the same way as the whole character, this character is referred to as a regular character (e.g. the compound character /you2/ and its phonetic radical: /you2/); otherwise, it is considered as an irregular character (e.g. the compound character /xiu4/ and its phonetic radical /you2/).

Although approximately 85% of Chinese characters are semantic–phonetic compounds (Perfetti and Tan, 1998; Zhu, 1988), in which the phonetic radical provides a cue for the whole-character pronunciation, less than 30% of them are regular characters (Tan and Perfetti, 1998). Thus, the majority of Chinese compounds are irregular characters. Several behavioral studies have found that reading irregular characters in Chinese was slower than reading regular characters (Yang and Shu, 2008; Zhang et al., 2003). Therefore, irregular character reading may not be cued by valid phonological-related information; that is, it appears to require address-based phonological processing (Balota and Ferraro, 1993). Several neuroimaging studies (Peng et al., 2004; Tan et al., 2001a) have also found that some brain areas were involved in the regularity effect, including the left inferior tempoparietal area (involved in the storage of phonological information), and the LMF G (particularly in addressed phonology, with irregular characters). Thus, the regularity effect reflects the unique characteristic of Chinese phonological processing.

In the current study, we sought to explore the neural basis of Chinese phonological processing in alphabetic language speakers (including English and Indonesian speakers) who learned Chinese as a second language. The pattern of neural activation associated with the regularity effect was compared between L2 learners and native Chinese speakers. According to the accommodation/assimilation hypothesis, if there is an accommodation-based pattern, we would expect to observe the additional recruitment of the right fusiform gyrus (Lee et al., 2004; Nelson et al., 2009; Tan et al., 2003), the left middle frontal gyrus (Liu et al., 2007; Perfetti and Liu, 2005; Tan et al., 2001a, 2005), and the dorsal aspect of the left inferior parietal lobe (Deng et al., 2011; Peng et al., 2004; Tan et al., 2005) in L2 learners. In contrast, if an assimilation-based pattern is applied, we would expect that regions relevant to the phonological processing of alphabetic languages would be activated, including the left inferior frontal gyrus (Bitan et al., 2007; Bokde et al., 2001; Bolger et al., 2005, 2008; Fiez et al., 1999; Gold and Buckner, 2002; Homae et al., 2002) and the ventral aspect of the left inferior parietal lobe (Bolger et al., 2005; Booth et al., 2002, 2006; Ravizza et al., 2004; Tan et al., 2005).

Material and methods

Participants

Twenty native alphabetic language speakers participated in a pilot behavioral test to select appropriate experimental stimuli. Participants were international students, and had been learning Chinese as L2 for one to two years in China. Selected from the same student group, another fifteen L2 learners (eight males, a mean age of 23 years, ranging from 19 to 30 years) took part in the following functional magnetic resonance imaging (fMRI) study. Their native languages were English or Indonesian, both of which are alphabetic languages.

Thirty native Chinese-speaking university students participated in the pilot behavioral study, and another 15 students (eight males, a mean age of 22.5 years, ranging from 19 to 25 years) took part in the following fMRI study.

All participants reported normal or corrected-to-normal vision. Written consent was obtained from each participant prior to the experiment. This study was conducted in the State Key Lab of Cognitive Neuroscience and Learning, Beijing Normal University, China, and was approved by the ethics committee of Beijing Normal University.

Design and materials

A mixed 2×2 factorial design was conducted, including one-within-subject factor: regularity (regular vs. irregular), and one between-subject factor: participant type (native Chinese speakers vs. L2 learners).

Seventy-two Chinese characters, equally consisting of two stimulus types: regular (reg) versus irregular (irreg) characters. Regular characters were those whose phonetic radical sounded the same as the whole-character, referring to the same initial consonant and compound vowel. Otherwise, the characters were classified as irregular characters. All characters were of high frequencies (a mean value of 60.98 occurrence per million), selected from level A and B in the vocabulary self-testing handbook of Hanyu Shuiping Kaoshi (HSK) (Pan, 2002). These characters all had left-right structures, with the phonetic radicals on the right side. The phonetic radical of each character was a single character. All the characters had unambiguous
meaning, i.e. they were not functional words. All characters had a low level of consistency, which was balanced between regular- and irregular-conditions, with a range from 0.06 to 0.4. As shown in Table 1, the average character frequencies and the number of strokes were not significantly different between regular and irregular conditions.

The pilot behavioral naming test confirmed the regularity effect in twenty L2 learners and thirty native Chinese speakers. Results of a paired-samples t-test for reaction time (RT) showed a significant regularity effect for both groups. Regular character reading was faster than irregular character reading (L2 learners: t(19) = 2.942, p < 0.01; native Chinese speakers: t(29) = 3.309, p < 0.01), mean reaction times were shown in Table 2.

fMRI procedure

Fig. 1 shows the arrangement of the whole fMRI scanning session and the presentation format of each trial. A block design was used for presenting stimuli. In the fMRI scanning session, there were four task blocks (two blocks for regular characters and two blocks for irregular characters), and four baseline blocks prior to each task block. There were 18 characters in each task block, resulting in a total of 36 characters for each type. The whole scanning session lasted 4.8 minutes.

Within each task trial, a visual character was presented for 1500 ms followed by a 500-ms blank, followed by the appearance of the next trial. Participants were instructed to pronounce the target character covertly. In the baseline blocks, the same presentation format was used. Within each trial, a fixation cross was presented instead of a character. Participants were asked to stare at the fixation without making any other response.

Homodyonic responses were acquired on a 3 T Siemens Trio MR system (Siemens Trio Magnetic Resonance Imaging system, Germany). Participants were instructed to keep still inside the scanner, and their heads were aligned to the center of the magnetic field. For each participant, three-dimensional anatomical images with high resolution were acquired using a Siemens magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence. For the functional imaging studies, a blood oxygen level-dependent (BOLD)-sensitive gradient echo-plane imaging (EPI) sequence was acquired. The following scan parameters were used: repetition time = 2000 ms, echo time = 30 ms, flip angle = 90°, matrix size = 64 × 64, field of view = 20 cm, slice thickness = 4 mm, gap = 0.8 mm, number of slices = 30. In addition, a high-resolution, T1-weighted three-dimensional image was acquired (acquisition gradient magnitude (MPRAGE) sequence. For the functional imaging studies, a blood oxygen level-dependent (BOLD)-sensitive gradient echo-plane imaging (EPI) sequence was acquired. The following scan parameters were used: repetition time = 2000 ms, echo time = 30 ms, flip angle = 90°, matrix size = 64 × 64, field of view = 20 cm, slice thickness = 4 mm, gap = 0.8 mm, number of slices = 30).

Image processing and statistical analysis were conducted by the Functional NeuroImage (AFNI) software package (Cox, 1996; Cox and Hyde, 1997; http://afni.nimh.nih.gov/afni/). Slice timing correction, motion correction, and temporal filtering of functional images were performed on each individual dataset. The MPRAGE anatomical scan was normalized to Talairach space (Talairach and Tournoux, 1988). The Talairach-aligned dataset was spatially smoothed by a 6-mm full-width half-maximum Gaussian kernel. General linear modeling (GLM) was used for single-subject analysis of functional images (deconvolution analysis), producing the hemodynamic response function (HRF) for each experimental condition. A group mask was created to remove voxels outside the brain, produced by multiplying masks from each participant to include only the voxels with valid signals.

A random effect group analysis was performed with two-way ANOVAs, including regularity as a fixed effect, and participant as a random effect. Monte Carlo simulations with AFNI’s ALPHASIM program were used to set the voxel-wise intensity threshold at p < 0.001 uncorrected, and the cluster size threshold at 2 contiguous voxels (voxel size: 3 × 3 × 3 mm³) for a corrected significance level of p < 0.01.

fMRI results

No explicit behavioral performances were recorded in the fMRI session because of the silent naming task. The fMRI data were averaged for the comparisons of characters vs. fixation within each group. Brain areas of significant activation are summarized in Table 3. The similar activation peaks between groups in character reading were mainly located in the right inferior frontal gyrus, bilateral occipitotemporal junction (fusiform gyrus, lingual gyrus, inferior and middle occipital gyrus), and the left cingulate gyrus. The amount of activated voxels in each region was consistently larger for L2 learners than for Chinese speakers. Fig. 2 shows activations in the OT regions for two groups. For L2 learners, additional activations were observed in the left medial frontal gyrus and the right inferior parietal lobule; while Chinese participants produced additional activations in the left precentral gyrus, left middle temporal gyrus, right superior temporal gyrus, right cingulate gyrus, and right insula.

Direct comparisons between regular and irregular characters in each group are shown in Table 4. For native Chinese speakers, reading irregular characters produced greater activations than reading regular ones in bilateral inferior frontal gyrus, left inferior parietal lobule, left precuneus, left superior temporal gyrus, and right posterior cingulate gyrus. In contrast, regular character reading produced greater activations in the right superior temporal gyrus, right inferior parietal lobule, left fusiform gyrus, and right cingulate gyrus. For L2 learners, reading irregular characters produced greater activations than reading regular characters in bilateral inferior frontal gyrus, left inferior parietal lobule, left middle temporal gyrus and right lingual gyrus; while reading regular characters induced greater activation in the left cingulate gyrus. Overall, the overlapping regions between two groups were found in the LIFG and LIPL, which were more activated in irregular character reading compared with regular character reading, but the activation peaks were slightly different. L2 learners showed activities in ventral LIFG [−49, 24, 4] (BA 44/45) and ventral LIPL [−49, −47, −22].

Table 1

Stimulus characteristics in all conditions.

<table>
<thead>
<tr>
<th></th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>52.04 (70.9)</td>
<td>60.92 (81.8)</td>
</tr>
<tr>
<td>Number of strokes</td>
<td>9.17 (2.5)</td>
<td>8.83 (1.7)</td>
</tr>
</tbody>
</table>

Note. Frequency values are occurrences per million. Standard deviations are in parentheses.

Table 2

Mean reaction times (ms) in the behavioral study.

<table>
<thead>
<tr>
<th></th>
<th>L2 learners</th>
<th>Chinese native speakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>564.4 (51.3)</td>
<td>5342 (53.1)</td>
</tr>
<tr>
<td>Irregular</td>
<td>571.3 (51.8)</td>
<td>5540 (56.6)</td>
</tr>
</tbody>
</table>

Note. Standard deviations are in parentheses.
Fig. 1. Arrangement of the whole fMRI scanning session and the presentation format of each trial.

22] (BA 40) [Fig. 3], while native Chinese speakers showed activities in dorsal LIFG [−39, 4, 33] (BA 9) and dorsal LIPL [−39, −49, 37] (BA 40) [Fig. 3].

Discussion

The present study examined the “accommodation/assimilation” hypothesis regarding the neural basis of phonological processing in second language reading. Particularly, we examined neural activation associated with the regularity effect in Chinese character reading among L2 learners whose first language was alphabetic. The current study had two major features: 1) the regularity effect was used to reveal the addressed phonological processing in Chinese; 2) our L2 participants learned Chinese as a second language in a class situation for a relatively long time, rather than a short-term training in the laboratory, and were compared with native Chinese speakers.

Overall, the current results revealed that L2 learners strongly recruited right occipitotemporal regions for Chinese reading, and the activation intensity in L2 learners was greater than that in native Chinese speakers. Regarding the regularity effect, L2 learners exhibited activations in the ventral aspects of the LIFG (BA 44/45) and the LIPL. In contrast, native Chinese speakers exhibited activations in the dorsal aspects of the LIFG (BA 9) and the LIPL. In accordance with our predictions, the current findings revealed that L2 learners exhibited brain activation suggesting both accommodation and assimilation patterns for Chinese characters reading.

Table 3

<table>
<thead>
<tr>
<th>Regions</th>
<th>BA</th>
<th>(x, y, z)</th>
<th>t</th>
<th>Vmnl (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R inferior frontal G./R precentral G.</td>
<td>6</td>
<td>(30, 1, 28)</td>
<td>7.54</td>
<td>4158</td>
</tr>
<tr>
<td>L precentral G.</td>
<td>6</td>
<td>(−4, 16, 43)</td>
<td>3.52</td>
<td>135</td>
</tr>
<tr>
<td>L medial frontal G.</td>
<td>40</td>
<td>(45, −33, 27)</td>
<td>3.71</td>
<td>54</td>
</tr>
<tr>
<td>R inferior parietal lobe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L middle temporal G.</td>
<td></td>
<td></td>
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<tr>
<td>L middle temporal G.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R superior temporal G.</td>
<td>38</td>
<td>(39, −23)</td>
<td>5.89</td>
<td>135</td>
</tr>
<tr>
<td>R superior temporal G.</td>
<td>19</td>
<td>(−36, −60, 10)</td>
<td>5.42</td>
<td>567</td>
</tr>
<tr>
<td>R inferior occipital G./R fusiform G./R lingual G./R middle occipital G.</td>
<td>18/19</td>
<td>(37, −69, −5)</td>
<td>10.46</td>
<td>111,483</td>
</tr>
<tr>
<td>L fusiform G./L inferior occipital G./L lingual G./R middle occipital G.</td>
<td>37</td>
<td>(−41, −52, −11)</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>L cuneus</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>L anterior cingulate G.</td>
<td>24</td>
<td>(−10, 28, −5)</td>
<td>4.81</td>
<td>2835</td>
</tr>
<tr>
<td>L cingulate G.</td>
<td>32</td>
<td>(−9, 24, 29)</td>
<td>3.56</td>
<td>108</td>
</tr>
<tr>
<td>R cingulate G.</td>
<td>13</td>
<td>(34, −29, 15)</td>
<td>16.08</td>
<td>999</td>
</tr>
</tbody>
</table>

Notes. G., gyrus. L, left; R, right. x, y, z are Talairach coordinates. Vmnl (mm³), volume of activated regions in unit of cubic mm. These brain areas exhibited peak activation for the comparison between character reading and baseline. Significance level of t-test was set at p<0.01, corrected for multiple comparisons.

Right occipitotemporal regions were activated in L2 learners for Chinese character reading, including the right lingual gyrus and right fusiform gyrus. Activation of the right fusiform gyrus was commonly found in Chinese reading. This region may be associated with visual spatial analysis (Chen et al., 2007; Cohen et al., 2004; Tan et al., 2001b), or related to storage of the holistic information of characters (Dien, 2009). The right lingual gyrus was also found to be a critical component in processing the logographic properties of Chinese characters (Kuo et al., 2004; Tan et al., 2001a, 2001b). The involvement of these regions were also reported in previous bilingual and training studies, in which English speakers learned Chinese as a second language (Deng et al., 2011; Liu et al., 2007; Nelson et al., 2009). Because the visual configuration of word forms is markedly different between alphabetic languages and logographic languages (such as Chinese), alphabetic language speakers need to make more efforts in visual–spatial processing of characters when processing Chinese. Activation increases in the right OT regions indicate an accommodation pattern in L2 learners for Chinese orthographic processing.

In terms of the greater activation in right occipitotemporal region for L2 learning, it is possible that L2 participants were not so familiar with Chinese characters relative to native speakers. However, relationship between proficiency and activation intensity of the right OT regions is still controversial. It was reported that there was a negative correlation between the right fusiform gyrus and reading skill in English, i.e. the OT activities decreased as the reading skill increased (Shaywitz et al., 2002; Turkeltaub et al., 2003). In a laboratory-based L2 learning study of Liu et al. (2007), after a very short period of learning (3-days) on Chinese characters, native English speakers activated bilateral fusiform gyrus for viewing Chinese. As compared with the novel characters, learned ones induced less activities in the right fusiform, indicating that activation intensities decreased with the progressive proficiency. However, opposite evidence was also reported. In Deng et al. (2011), activations in the bilateral lingual gyrus were greater at the end of the fourth week's training than those at the end of the second week's training. In addition, Xue et al. (2006) reported a non-linear change of right OT activities during lexical training by showing a decreased activation after word-form learning but an increased activation after semantic and phonological learning. To our knowledge, the proficiency explanation has not been tested in L2 learners with different L2 proficiencies and a relatively long time for the L2 learning in terms of the activation of right OT region. In our present results, L2 learners all have learned...
Chinese for at least one year in China and they showed greater OT activities in Chinese processing comparing with native Chinese speakers. Current findings could not exclude the possibility of proficiency effect on the OT activation in L2 Learner, i.e. increased OT activities might be due to their low proficiency in this new language system. Further studies are needed to test higher skilled samples of L2 learners as comparison, so as to directly examine the influence of L2 proficiency on right OT’s activation pattern.

In the current study, participants from both groups recruited greater activity in the left inferior parietal lobule for the irregular character reading minus regular character reading. However, peak activation was more ventral for L2 learners, and more dorsal for native Chinese speakers. Several studies have suggested that the ventral aspect of the IPL plays an important role in GPC routes (Bolger et al., 2005; Booth et al., 2002, 2006; Tan et al., 2005) and phonological encoding-recoding processes (Ravizza et al., 2004) in English. However, as proposed by Tan et al. (2005), the dorsal aspect of the left inferior parietal region is more important in Chinese reading, and this region may be associated with temporary phonological storage of Chinese characters. In previous training studies, participants learned Chinese for a very short period of time, and failed to show activation in dorsal IPL (Deng et al., 2011; Liu et al., 2007). Interestingly, our participants continuously learned Chinese as their second language for at least one year before the experiment, and also showed no activation in Chinese compound characters could be considered as similar as the GPC rules in alphabetic languages. Previous behavioral results showed that reading regular words (i.e. words follow the GPC rules) is faster than reading irregular words (i.e. words do not follow the GPC rules) in alphabetic lexical decision and naming tasks (Coltheart, 1978; Coltheart et al., 1993; Coltheart et al., 2001; Jared, 2002). Similarly, reading regular Chinese characters (i.e. identical pronunciation between phonetic radical and the whole character) took a shorter time than reading irregular characters (i.e. phonetic radical sounded differently from the whole character) (Yang and Shu, 2008; Zhang et al., 2003). Some neuroimaging studies also suggested a common network responsible for the sublexical processing across English and Chinese language systems, covering left medial frontal gyrus, left inferior/superior frontal gyrus, bilateral superior temporal gyrus, right inferior parietal lobule, and left cingulate cortex (English: Bender et al., 2005; Bolger et al., 2008; Fiez et al., 1999; Chinese: Tan et al., 2001a; Peng et al., 2004), however, there still existed language-specific areas just as discussed above, ventral aspects of inferior parietal regions for alphabetic processing while dorsal aspects for Chinese processing. Thus, in our study, the involvement of ventral

Although Chinese characters lack GPC rules, the regularity effect of Chinese in fact relies critically on sublexical processing (or the interaction of sublexical and lexical phonological processing). Present L2 learners recruited ventral IPL to process Chinese regularity, suggesting there were some similarities in the sublexical processing between Chinese and alphabetic language systems. Zhou and Marslen-Wilson (1999) suggested that the phonetic radical-sound correspondences in Chinese compound characters could be considered as similar as the GPC rules in alphabetic languages. Previous behavioral results showed that reading regular words (i.e. words follow the GPC rules) is faster than reading irregular words (i.e. words do not follow the GPC rules) in alphabetic lexical decision and naming tasks (Coltheart, 1978; Coltheart et al., 1993; Coltheart et al., 2001; Jared, 2002). Similarly, reading regular Chinese characters (i.e. identical pronunciation between phonetic radical and the whole character) took a shorter time than reading irregular characters (i.e. phonetic radical sounded differently from the whole character) (Yang and Shu, 2008; Zhang et al., 2003). Some neuroimaging studies also suggested a common network responsible for the sublexical processing across English and Chinese language systems, covering left medial frontal gyrus, left inferior/superior frontal gyrus, bilateral superior temporal gyrus, right inferior parietal lobule, and left cingulate cortex (English: Bender et al., 2005; Bolger et al., 2008; Fiez et al., 1999; Chinese: Tan et al., 2001a; Peng et al., 2004), however, there still existed language-specific areas just as discussed above, ventral aspects of inferior parietal regions for alphabetic processing while dorsal aspects for Chinese processing. Thus, in our study, the involvement of ventral

### Table 4

<table>
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<th>L2 learners</th>
<th></th>
<th></th>
<th>Native Chinese speakers</th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>BA (x, y, z) t Vmul (mm³)</td>
<td>L2 learners</td>
<td></td>
<td></td>
<td>Native Chinese speakers</td>
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<tr>
<td>Irreg &gt; Reg</td>
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<tr>
<td>L medial frontal G. 6</td>
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<tr>
<td>L inferior frontal G. 44</td>
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<tr>
<td>L inferior parietal lobule 40</td>
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<tr>
<td>L precuneus 18</td>
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<tr>
<td>L superior temporal G. 22</td>
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<td>R lingual G. 18</td>
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<td>R posterior cingulate G. 30</td>
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<td>R superior temporal G. 38</td>
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<td>R inferior parietal lobule 40</td>
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<td>L fusiform G. 20</td>
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<td>R cingulate G. 24</td>
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<td>L cingulate G. 3</td>
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Note: G., gyrus; L, left; R, right. x, y, z are Talairach coordinates. Vmul (mm³), volume of activated regions in unit of cubic mm. These brain areas exhibited peak activation for irregular character reading minus regular character reading. Significance level of t-test was set at p<0.01, corrected for multiple comparisons.
IPL for reading Chinese in L2 learner presented an alphabetic-specific activation pattern, indicating an assimilation mechanism applied by L2 learners to process Chinese regularity.

A third region that L2 learners recruited for Chinese character reading was the LIFG. Similar finding was also reported in a recent training study (Deng et al., 2011). The LIFG is thought to play an important role in grapheme-to-phoneme conversions and phonemic processing in alphabetic languages (Bokde et al., 2001; Bolger et al., 2005, 2008; Fiez et al., 1999; Gold and Buckner, 2002; Homae et al., 2002). The current recruitment of this region in L2 learners also suggests an assimilation mechanism involved in Chinese reading. Together with our finding in ventral IPL, these results suggest that L2 learners may utilize existing neural networks associated with their native language to access phonology from orthography, especially for irregular character reading, resulting in the robust assimilation pattern we observed in these two regions.

The “accommodation/assimilation” hypothesis has given a better explanation to the present L2 mechanism. But there were some other possibilities inducing the current brain activities. Previous studies reported increasing IPL and LIFG activities accompanied greater task difficulties (Assmus et al., 2005; Lewandowska et al., 2010). Because the phonetic radical did not provide valid phonological information for the whole character’s sound, reading irregular characters was more difficult than reading regular ones in our present study. Then, the present robust activations in these regions for the comparisons between irregular- and regular-conditions might be due to more effortful processing for irregular character reading.

Previous alphabetic studies reported that responding to conflicting information in language processing (such as reading more inconsistent/irregular words) activated regions of left inferior/middle frontal gyrus (Fiez et al., 1999; Herbst et al., 1997; Katz et al., 2005), left superior/middle temporal gyrus (Bolger et al., 2008), left superior/inferior parietal lobule (Binder et al., 2005; Bolger et al., 2008), and left medial frontal gyrus/anterior cingulate cortex (Binder et al., 2005). As to our experiment, conflicting information exists in the irregular characters, in which phonetic radicals sound differently from the whole characters. Therefore, the two groups of current participants both recruited the brain regions responsible for conflict resolution for Chinese irregular character reading, such as the IPL, left medial frontal gyrus and left cingulate gyrus, indicating that the current neural activation pattern in L2 learners might be associated with the processing of conflicting information.

In our present experimental design, there was no L1 effect of native alphabetic processing, and we compared current L2 activities with the converging findings in previous studies of alphabetic processing. If L1 effect was taken into account, the inferences of L2 mechanism based on the accommodation/assimilation hypothesis would be more powerful.

**Conclusions**

The current study explored neural activation related to the regularity effect in both L2 learners and native Chinese speakers, to examine how a later learned language becomes organized in the brain. The present results suggested that L2 learners utilized both accommodation and assimilation patterns in Chinese processing. They exhibited activation in right occipitotemporal region (such as the right fusiform gyrus, right lingual gyrus) for orthographic processing of Chinese, reflecting an accommodation pattern. L2 learners also induced alphabetic-specific areas of ventral aspects of the IPL and LIFG for phonological processing of Chinese, reflecting an assimilation pattern. Further studies are required to examine whether these accommodation/assimilation mechanisms are independent of language experience by recruiting English–Chinese bilinguals with higher reading skills in the Chinese, and to examine the possible long-term changes of L2 processing mechanisms.

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References


