Cerebral mechanisms for different second language writing systems

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ABSTRACT

In this fMRI study, we examined the cerebral processing associated with second language (L2) reading in different writing systems in late L2 learners. To examine the impacts of cross-linguistic differences between the first language (L1) and L2 on learning to read in L2, we employed a bidirectional approach and compared brain activation during single word processing in two groups of late L2 readers: (1) L2 readers of English whose L1 was Japanese (Japanese-L1/English-L2) and (2) L2 readers of Japanese (of syllabic Kana only) whose L1 was English (English-L1/Japanese-L2). During English reading, the L2 readers of English (Japanese-L1/English-L2) exhibited stronger activation in the left superior parietal lobe/supramarginal gyrus, relative to the L1 readers of English (English-L1/English-L2). This is a region considered to be involved in phonological processing. The increased activation in the Japanese-L1/English-L2 group likely reflects the increased cognitive load associated with L2 English reading, possibly because L1 readers of Kana, which has an extremely regular orthography, may need to adjust to the greater phonological demands of the irregular L2 English orthography. In contrast, during Kana reading, the L2 readers of Japanese Kana (English-L1/Japanese-L2) exhibited stronger activation in the lingual gyrus in both the left and right hemispheres compared to the L1 readers of Kana (Japanese-L1/English-L2). This additional activation is likely to reflect the lower level of visual familiarity to the L2 symbols in the English-L1/Japanese-L2 group; Kana symbols are uniquely used only in Japan, whereas Roman alphabetic symbols are seen nearly everywhere. These findings, bolstered by significant relationships between the activation of the identified regions and cognitive competence, suggest that the cerebral mechanisms for L2 reading in late learners depends both on which language is their L1 and which language to be learnt as their L2. Educational implications of these results are discussed.

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1. Introduction

With the advent of globalization, learning to read one or more second languages (L2) fluently has become increasingly important in the modern world. In many countries (e.g. the USA and Japan), L2 education does not officially start until the age of 10–12, well beyond the most receptive period for language acquisition (Au, Knightly, Jun, & Oh, 2002; Johnson & Newport, 1989; Lenneberg, 1967). Hence, late L2 learners seldom fully master L2 phonology as regards speech perception and speech production (see review by Bolger, Perfetti, & Schneider, 2005; Flege, 1991; Long, 1990; Newport, 1990). However, unlike listening or speaking, reading and writing are recent cultural developments (Lawler, 2001), and thus may require explicit and intensive learning not only for the first language (L1) but also for L2. Therefore, late L2 learners are only likely to be able to achieve native-like proficiency in L2 reading after a great deal of effort.

Writing systems differ widely in the way language units are represented (Bolger, Perfetti, & Schneider, 2005). In reading, it is crucial to map letters and letter combinations (orthography) onto their sounds (phonology), but grapheme-phoneme conversion varies according to orthographic regularity, even when the same orthography (e.g. the Roman alphabet) is used to represent different written languages. For example, Italian and English both use the same Roman alphabet, but the Italian orthography is considerably more regular/transparent than the English orthography: “d” can be read only as /d/ in Italian, but in English, “d” can be read as /d/ (“bed”), /dʒ/ (“procedure”), or not pronounced at all (“Wednesday”). Consequently, L2 readers of English need to learn arbitrary orthographic patterns and an additional range of phonological representations present in English words. Thus, for Italian L1 readers, learning to read English is inevitably more demanding cognitively than for English L1 readers learning to read Italian.

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Effects of orthographic regularity are evident in early developmental patterns of word reading. Seymour, Aro, & Erskine (2003) compared the rate of reading acquisition in age-matched children from different European countries, and showed that word reading can be acquired faster by readers of regular orthographies (e.g., Italian, Spanish, Finnish) than by readers of the irregular English orthography. These linguistic differences are consistent with the psycholinguistic grain size theory of reading (Ziegler and Goswami 2005), and indicates that word reading in an irregular orthography may be cognitively more demanding for reading beginners, and potentially even more so for late L2 learners.

In addition to orthographic regularity, visual features of symbols can vary widely between different writing systems. For example, when L1 English readers learn to read an L2 such as Japanese or Russian, the familiar L1 symbols of the Roman alphabet are replaced with unfamiliar L2 symbols in the target language (Japanese Kana or Russian Cyrillic). However, in these phonographic writing systems, symbols are still fundamentally mapped to sounds as phonemes and syllables. More radically, in logographs, such as Japanese Kanji or Chinese Hanzi, no simple mappings from symbols to sounds exist at all. Therefore, when visual features of symbols are different between late readers’ L1 and L2, successful L2 reading requires them to accommodate to the additional visual demands of the L2 script (script (Nelson, Liu, Fiez, and Perfetti 2009)), since applying L1 reading strategies to a new writing system will be ineffective. That is, phonological decoding employed in reading alphabetic English words simply cannot be applied to logographic reading.

A recent fMRI study has highlighted brain regions significantly more engaged in L2 readers compared to L1 readers (Zhao et al., 2011). In this study, L2 readers of Chinese, who had L1s with alphabetic systems (e.g., English), exhibited stronger activation during logographic word processing in the right visual cortex (including fusiform gyrus) compared to L1 readers of Chinese. This L2 group effect (greater activation in L2 readers than L1 readers) indicates that the L2 readers of Chinese had adapted to the greater visual demands of the Chinese characters. Clearly, the Roman alphabet is far less visually complex than the logograph. Even in skilled logographic L1 readers, the logographic symbols/words (e.g., Japanese Kanji) activated the right visual cortex more strongly than non-logographic symbols (e.g., Japanese Kana) (Koyama, Stein, Stoodley, & Hansen, 2011; Nakamura, Dehaene, Jobert, Le Bihan, & Koudier, 2005), emphasizing that visual features of symbols and words exert strong influences on visual networks.

To date, differences in cerebral mechanisms between L1 readers and L2 readers have been mainly investigated by targeting one writing system as the L2 (e.g., Chee, Tan, & Thiel, 1999; Klein et al., 2006; Kovelman, Baker, & Petito, 2007; Leonard et al., 2010; Marian et al., 2007; Parker et al., 2012; Yokoyama et al., 2006). However, this approach does not fully allow us to understand the impact of cross-linguistic differences between L1 and L2 writing systems on L2 reading in late learners, whose neural networks for reading have been established based on their L1 reading. Here, we employed a bidirectional approach and examined patterns of brain activation in two groups of late L2 readers: (1) L2 readers of English whose L1 was Japanese; and (2) L2 readers of Japanese (of syllabic Kana only) whose L1 was English.

For both English and Japanese Kana scripts, the symbols are visually simple (relative to logographic symbols) and mapped onto sounds, but these two writing systems are very different in their level of orthographic regularity: English has an irregular orthography, whereas Kana is extremely regular with nearly one-to-one mapping with only a few exceptions (none of which were used in this experiment). Hence, we postulated that the orthographic difference between L1 and L2 writing systems would exert an impact on the cerebral mechanisms underlying L2 reading only in the L2 group learning English, because their L2 orthography (English) was far more irregular than their L1 orthography (Kana).

2. Methods
2.1. Participants
Two groups of late L2 readers participated in this study: fifteen native Japanese readers who had learnt English as L2 (Japanese-L1/English-L2 group, “J1/E2” group; mean ± SD = 29.3 ± 6.4 years) and fourteen native English readers who had learnt Japanese Kana as L2 (English-L1/Japanese-L2 group, “E1/J2” group; mean ± SD = 26.2 ± 5.7 years). They were all right-handed, as measured by the Annett Handedness Questionnaire (Annett, 1970). Participants reported no history of psychiatric disorders or learning disability (including dyslexia). A questionnaire confirmed that no one in either group started learning their L2 language before the age of 12. Thus, all participants were defined as late L2 readers. In addition, all participants had L2 experience at university abroad (e.g. on exchange programs) for at least 6 months (i.e. English-L2 readers in the UK; Japanese-L2 readers in Japan). The study was approved by the Oxfordshire Research Ethics Committee.

At the time of the current study (both cognitive testing and fMRI scanning), participants in the J1/E2 group were either full-time students (N=5) or exchange students (N=10) at universities in the UK, whereas those in the E1/J2 group were full-time students who were studying Japanese at universities in Oxford. In addition, all participants in the E1/J2 group had learnt Japanese at university in Japan (e.g. on exchange programs) at least for 6 months.

2.2. Cognitive measures (Tasks performed outside the scanner)
Single word reading competence was assessed for English by the WRAT-III (Wilkinson, 1993) and for Japanese Kana by the Kana Word Reading test (Koyama, Hansen, & Stein, 2008). Additionally, we administered the Kanji Word Reading test, a measure of word reading in the logographic Japanese script (Koyama et al., 2008). Nonverbal IQ was measured using the Raven’s Advanced Progressive Matrices (Raven, Raven, & Court, 1998). We administered two short-term memory tests. Phonological short-term memory was measured by nonword repetition tasks – the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) for English sounds, and nonword repetition in morae (Koyama et al., 2008) for Japanese sounds. Visual short-term memory was measured by the Visual Patterns Test (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). It should be noted that the Kana Word Reading, Kanji Word Reading and nonword repetition tasks in Japanese were not standardized measures. We therefore used raw scores or percent accuracy for further analysis.

2.3. Tasks performed in the scanner
Participants performed a phonological one-back matching task for both Japanese Kana words and English words. Fig. 1 illustrates the task paradigm and the conditions of interest (words printed in lower case English and in Japanese syllabic Kana). Participants were instructed to press a button with their right index finger if successively presented words were phonologically identical (“Whenever you see two words in succession that sound the same, press the button”). To minimize visual strategies during the phonological one-back matching task, successive words were also printed in alternating fonts that were significantly different (regular versus italic for English words; Mincho vs. Gyosho for Kana words). This encouraged covert articulation and subsequent phonological encoding. All words were four characters long and represented high frequency nouns, based on the Amano and Kondo (1999) norms for Japanese Kana words, and frequency norms by Kocera and Francis (1997) for English words. For Kana words, visual familiarity ratings were examined to exclude any word that is more commonly printed in logographic Kanji (see details in Koyama et al., 2011).

The paradigm was a block design with alternating 24 s task blocks and 15 s rest blocks. In the rest block, a small red fixation point was visible at the center of the visual display. In the task block, 24 words were presented at a rate of 1/second, with an onscreen duration of 250 ms and a blank period of 750 ms between words. Within each task block, 3–5 of the 24 words were phonologically identical and required a button response. The participants were encouraged to respond as quickly and accurately as possible. Prior to the scan session, participants performed a computerized practice run outside the scanner to ensure task familiarity. In order to prevent word-specific practice effects, the word stimuli used in the practice run were different from the words used in the in-scanner task.

Even though words were presented in alternating fonts or style for both word conditions, the possibility that participants employed some degree of visual matching strategies cannot be entirely ruled out. Hence, the two groups performed a further control task that was a purely visual one-back matching task involving visually unfamiliar, unpronounceable, but ecologically valid, Tibetan letter strings. (Note that no Tibetan symbols similar to symbols present in either English or Kana were selected). The paradigm applied to this visual task was the same as the
3. Results

3.1. Cognitive measures (Performance outside the scanner)

Table 1 gives a summary of the demographic and cognitive measures (performed outside the scanner) for each group. It can be seen that the two groups were matched in age, gender, intellectual competence, and visual short-term memory.

3.1.1. Word reading tasks

Although each L2 group achieved high-level performance in their L2 word reading, the accuracy was still higher for L1 group than L2 group. For the WRAT (total number of words=44), the mean accuracy ± SD was 37.0 ± 3.6 in the E1/J2 group and 31.5 ± 5.5 in the J1/E2 group (t=3.2, p<0.01). For Kana (total number of words=20), the mean accuracy ± SD was 23.9 ± 2.0 in the J1/E2 group and 18.2 ± 1.3 in the E1/J2 group (t-test was not performed for Kana accuracy due to a ceiling effect in both groups). This level of accuracy for Kana reading (i.e., no errors made by the native Japanese speakers; a small standard deviation even in the non-native Japanese speakers) confirms that Kana has an extremely regular orthography. As with the fluency, the response time was significantly shorter (i.e. more fluent) in the L1 group than the L2 group. For WRAT, the mean response time ± SD was 62.2 ± 11.1 s in the E1/J2 group and 76.4 ± 19.8 s in the J1/E2 group (t=2.4, p<0.05). For Kana, the mean response time ± SD was 35.6 ± 7.9 s in the J1/E2 group and 67.0 ± 21.2 s in the E1/J2 group (t=5.4, p<0.01).

For writing systems with regular orthography, reading fluency, rather than reading accuracy, may be a more sensitive index of reading proficiency (De Luca, Zeri, Spinelli, & Zoccolotti, 2010). This can be more evident in Kana, a writing system with extremely regular orthography (Seki, Kassai, Uchiyama, & Koeda, 2008). In the current study, the L2 readers of Japanese (i.e., E1/L2 group) had significantly slower RT for Kana reading relative to the L1 readers of Japanese (i.e., J1/E2 group), suggesting that their

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Japanese-L1/English-L2 Mean (SD)</th>
<th>Japanese-L1/English-L2 Mean (SD)</th>
<th>Group difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>29.3 (6.4)</td>
<td>262.0 (5.7)</td>
<td>t=1.4, N.S.</td>
</tr>
<tr>
<td>Sex</td>
<td>M 46/11 F</td>
<td>4M/10 F</td>
<td>χ²=0.1, N.S.</td>
</tr>
<tr>
<td>Raven (max=36)</td>
<td>291.0 (5.8)</td>
<td>273.0 (4.6)</td>
<td>t=0.9, N.S.</td>
</tr>
<tr>
<td>WRAT (max=44)</td>
<td>315.0 (5.5)</td>
<td>370.0 (3.6)</td>
<td>t=3.2, p&lt;0.01</td>
</tr>
<tr>
<td>WRAT RT (s)</td>
<td>76.4 (19.8)</td>
<td>62.2 (11.1)</td>
<td>t=2.4, p&lt;0.05</td>
</tr>
<tr>
<td>Kana (max=20)</td>
<td>20.0 (0.0)</td>
<td>18.2 (1.3)</td>
<td>No statistical test</td>
</tr>
<tr>
<td>Kana RT (s)</td>
<td>35.6 (7.9)</td>
<td>67.0 (21.2)</td>
<td>t=5.4, p&lt;0.01</td>
</tr>
<tr>
<td>Kanji (max=60)</td>
<td>568.0 (2.5)</td>
<td>211.0 (6.1)</td>
<td>t=20.9, p&lt;0.001</td>
</tr>
<tr>
<td>NWRepEng (max=18)</td>
<td>13.3 (2.7)</td>
<td>15.9 (1.5)</td>
<td>t=3.0, p&lt;0.01</td>
</tr>
<tr>
<td>NWRepplap (max=40)</td>
<td>32.2 (4.5)</td>
<td>28.5 (3.2)</td>
<td>t=2.5, p&lt;0.05</td>
</tr>
<tr>
<td>VPT (max=42)</td>
<td>212.0 (3.9)</td>
<td>234.0 (2.3)</td>
<td>t=1.8, N.S.</td>
</tr>
</tbody>
</table>

proficiency of L2 Kana reading did not reach the native-level despite their highly accurate performance. Hence, individuals in both L2 groups were not equal-bilinguals between L1 and L2, with their L1 as the more dominant language. With respect to logographic Kanji (total number of words = 60), the mean accuracy score was significantly lower in the Japanese-L2 group (mean score ± SD = 21.1 ± 6.1) than the Japanese-L1 group (mean score ± SD = 56.8 ± 2.5), with t = 20.9, p < 0.001. Because the two groups’ accuracy performance on Kanji reading was not comparable, Kanji stimuli were not used in the fMRI experiments.

3.1.2. Non-verbal IQ and memory tasks

All participants’ scores on the Raven’s Advanced Progressive Matrices were within the normal range (mean score ± SD = 29.1 ± 5.8 and 27.3 ± 4.6 for the J1/E2 and the E1/J2 group, respectively). This confirmed no inclusion of intellectually impaired participants in the study. No group differences were observed for either the Raven’s Advanced Progressive Matrices (t = 0.9, p = 0.37) or the Visual Patterns Test (total number of patterns = 42, the mean accuracy ± SD = 212.1 ± 3.9 in the E1/J2 group and 23.4 ± 2.3 in the J1/E2 group; t = 1.8, p = 0.08) for the nonword repetition task using English sounds, the mean score was significantly higher in the E1/J2 group (mean score ± SD = 15.9 ± 1.5) than the J1/E2 group (mean score ± SD = 13.3 ± 2.7), with t = 3.0, p < 0.01. Similarly, for the nonword repetition task using Japanese morae, the J1/E2 group mean score was significantly higher (mean score ± SD = 32.2 ± 4.5) than the E1/J2 group (mean score ± SD = 28.5 ± 3.2), with t = 2.5, p < 0.05.

3.2. Task performance in the scanner

For the main phonological one-back matching task, no differences were observed between L1 and L2 groups in either accuracy or response time for word reading. More specifically, the mean accuracy (%) ± SD for English words was 97.8 ± 0.8 in the E1/J2 group and 94.67 ± 1.4 in the J1/E2 group (t = 1.98, p = 0.06), whereas the mean accuracy (%) ± SD for Kana words was 96.3 ± 0.8 in the J1/E2 group and 95.1 ± 1.3 in the E1/J2 group (t = 0.75, p = 0.46). The mean response time (s) ± SD for English words was 0.51 ± 0.01 in the E1/J2 group and 0.52 ± 0.02 in the J1/E2 group (t = 0.25, p = 0.81), whereas the mean response time (s) for Kana words was 0.51 ± 0.02 in the J1/E2 group and 0.53 ± 0.01 in the E1/J2 group (t = 0.61, p = 0.55). These results suggest that any group differences recorded in brain activation were not likely to have arisen purely from differences in task difficulty. For the control visual one-back matching task, no group difference was observed in either the mean accuracy (%) or mean response time (s): mean accuracy (%) ± SD = 86.2 ± 10.4 in the J1/E2 group and 87.4 ± 9.6 in the E1/J2 group; t = 0.32, p = 0.75; mean reaction time (s) ± SD = 0.68 ± 0.04 in the J1/E2 group and 0.66 ± 0.03 in the E1/J2 group; t = 1.51, p = 0.14.

3.3. Brain activation

3.3.1. Whole-brain analysis

During the task of interest in the current study, the phonological one-match task, both groups significantly activated brain regions considered to be parts of the reading network (Pugh et al., 2000) for both word conditions (Fig. 2, Table 2 for English words, and Table 3 for Kana words). Despite the similarities in activation patterns, there was greater activation in the L2 group than in the L1 group for the L2 word condition (the L2 group effect). More interestingly, the identified clusters/regions showing the L2 group effect were located in functionally different networks for the two groups (Table 4). Specifically, for English words, the left superior parietal lobule, extending into the supramarginal gyrus (L-SPL/SMG, peak MNI x = −35, y = −52, z = 38, z = 31; 83 voxels) exhibited greater activation in the J1/E2 group than the E1/J2 group (Table 4 and Fig. 3A). For Kana words, the left lingual gyrus, extending into the lateral occipital complex (L-LG/LOC, peak MNI x = −16, y = −72, z = 12, Z = 4.0; 264 voxels) exhibited greater activation in the E1/J2 group than the J1/E2 group (Table 4 and Fig. 4A). Similarly, this L2 group effect for Kana words was observed in the right lingual gyrus (R-LG, peak MNI x = 8, y = −72, z = 12, Z = 4.3, 219 voxels) but this R-LG cluster did not

Figure Legend: [Japanese-L1/English-L2 Group] [English-L1/English-L2 Group]

Fig. 2. Brain regions activated during (A) English word condition and (B) Kana word condition. L1 group and L2 group activated largely overlapping cortical regions within the known reading network: clusters in red and blue represent activation patterns in the Japanese-L1/English-L2 group and the English-L1/Japanese-L2 group, respectively. Z > 2.3, p < 0.05, corrected (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).
Table 2

Peak MNI coordinates of significant clusters for English words.

<table>
<thead>
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<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>SMA/AC</td>
<td>−2</td>
<td>4</td>
</tr>
<tr>
<td>L-IFG/PCG</td>
<td>−44</td>
<td>8</td>
</tr>
<tr>
<td>R-IFG/PCG</td>
<td>48</td>
<td>6</td>
</tr>
<tr>
<td>L-IPL/SPL</td>
<td>24</td>
<td>−62</td>
</tr>
<tr>
<td>L-SMG*</td>
<td>−42</td>
<td>−38</td>
</tr>
<tr>
<td>R-IPL/SPL</td>
<td>30</td>
<td>−66</td>
</tr>
<tr>
<td>R-SMG*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-FFG/LOC</td>
<td>−40</td>
<td>−52</td>
</tr>
<tr>
<td>R-FFG/LOC</td>
<td>44</td>
<td>−68</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>8</td>
<td>−76</td>
</tr>
</tbody>
</table>

L1 = first language, L2 = second language, L = left, R = right, SMA/AC = supplementary motor area/anterior cingulate, IFG/PCG = inferior frontal gyrus/precentral gyrus, IPL/SPL = inferior parietal lobule/superior parietal lobule, SMG = supramarginal gyrus, FFG/LOC = fusiform gyrus/ lateral occipital complex, vox = voxel; Z > 2.3, p < 0.05, corrected. * Sub-cluster.

Table 3

Peak MNI coordinates of significant activation clusters for Kana words.

<table>
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<tbody>
<tr>
<td></td>
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<td>−76</td>
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<td>−74</td>
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L1 = first language, L2 = second language, L = left, R = right, SMA/AC = supplementary motor area/anterior cingulate, IFG/PCG = inferior frontal gyrus/precentral gyrus, IPL/SPL = inferior parietal lobule/superior parietal lobule, SMG = supramarginal gyrus, FFG/LOC = fusiform gyrus/lateral occipital complex, vox = voxel; Z > 2.3, p < 0.05, corrected. * Sub-cluster.

Table 4

Peak MNI coordinates of significant differences between the L1 and L2 groups.

<table>
<thead>
<tr>
<th>L2 Group &gt; L1 Group</th>
<th>English words</th>
<th>Kana words</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>L-SPL/SMG</td>
<td>−35</td>
<td>52</td>
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<tr>
<td>L-LG</td>
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<tr>
<td>L-LOC*</td>
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<tr>
<td>R-LG</td>
<td>8</td>
<td>72</td>
</tr>
</tbody>
</table>

L1 = first language, L2 = second language, L = left, R = right, SPL/SMG = superior parietal lobule/supramarginal gyrus, LG = lingual gyrus, LOC = lateral occipital complex. * Sub-region of L-LG, Z > 2.3, p < 0.05, corrected.
processed Kana words. Similar to L-LG/LOC, no significant activation of this region was reported for either Kana words or English words in either group.

3.4. Brain-behavior relationships

We examined whether the individual differences in literacy and cognitive abilities measured outside the scanner were correlated with the BOLD signal change in these regions/clusters (L-SPL/SMG, L-LG/LOC, and R-LG). Each region’s activity was plotted as a function of competence in word reading (both response time and accuracy), phonological short-term memory (the accuracy of the NWRep in either English or Japanese), and visual short-term memory (accuracy in the Visual Patterns Test). The response time, rather than the accuracy, was used to represent word reading (accuracy for the WRAT; only the response time for Kana Word Reading) for Kana word reading and those who had higher visual short-term memory tended to exhibit stronger bilateral LG activation for L2 English words. Such brain-behavior relationships were not seen in the E1/J2 group. Note that the E1/J2 group showed a trend (statistically non-significant) for the opposite brain-behavior pattern, a negative relationship for phonological short-term memory. A measure of visual short-term memory, the VPT, was not a significant predictor of L-LPL/SMG activation in either group (Fig. 3E).

The BOLD signal changes in L-LG/LOC and R-LG during Kana reading correlated positively with the Kana Word Reading response time in the E1/J2 group: $R^2 = 0.32$, $p < 0.05$ in Fig. 4C; R-LG, $R^2 = 0.57$, $p < 0.01$ in Fig. 5C. Similarly, they positively correlated with the VPT accuracy in the E1/J2 group: L-LG/LOC, $R^2 = 0.49$, $p < 0.01$ in Fig. 4E; R-LG, $R^2 = 0.47$, $p < 0.01$ in Fig. 5E. Thus, the E1/J2 readers with longer response times (i.e. less fluent reading) for Kana word reading and those who had higher visual short-term memory tended to exhibit stronger bilateral LG activation for L2 Kana words. Such significant brain-behavior relationships were seen only for visual short-term memory in the J1/E2 group ($R^2 = 0.30$, $p < 0.05$ for L-LG/LOC; $R^2 = 0.31$, $p < 0.50$ for R-LG). A measure of phonological short-term memory, the NWRep in Japanese, was not significantly correlated with either L-LG/LOC or R-LG activation in either group (Figs. 4 and 5D).

3.5. A secondary analysis

To attempt to further clarify the activation pattern of the lingual gyrus, which showed the L2 group effect for the Kana condition but did not show significant activation during either the Kana or English condition, we performed a secondary region of interest analysis. Both L-LG/LOC and R-LOC were examined during...
the phonological and visual tasks (i.e., visually unfamiliar and unpronounceable Tibetan letter strings). In the J1/E2 group, the activation in L-LG/LOC was highest in the Tibetan control condition (relative to Kana, \( t = 4.21, p < 0.01 \); relative to English, \( t = 3.76, p < 0.01 \)) and there was no difference in L-LG/LOC activation between L1 Kana and L2 English. This pattern was not observed in R-LG where the activation did not differ among the three conditions. In the E1/J2 group, the activation in L-LG/LOC was significantly higher for the Tibetan control condition than the L1 English condition (\( t = 2.81, p < 0.05 \)) but not the L2 Kana condition. No significant group difference was noted between the L1 English and the L2 Kana conditions. Similar to L-LG/LOC, R-LG showed no difference among the three conditions in either group.

4. Discussion

We compared cerebral activity in response to single word reading of alphabetic English and syllabic Japanese Kana between L1 and L2 groups. During L2 word reading, each L2 group recruited brain regions similar to those employed by the corresponding L1 group. More importantly, however, we found different patterns associated with the L2 group effect (greater activation in the L2 group than the L1 group) depending on the writing system being learned as L2. Specifically, the Japanese-L1/English-L2 (J1/E2) group exhibited stronger activation in the left superior parietal lobule/supramarginal gyrus (L-SPL/SMG) during reading of English words, whereas the English-L1/Japanese-L2 (E1/J2) group exhibited stronger activation in the lingual gyrus in both left and right hemispheres (L-LG and R-LG) during reading of Kana words. These results suggest that different cortical areas are more strongly recruited in late L2 readers than L1 readers depending on the particular qualities of the language/writing system being learnt as L2. Considering that both L2 groups were non-equal bilingual groups (i.e., L2 is the less dominant or weaker language of the two), the increased activation associated with the L2 group effect is likely to reflect increased cognitive loads to achieve L2 reading in the L2 groups.

4.1. The L2 group effect for English words

The L2 group effect during the English word condition was observed in L-SPL/SMG, encompassing superior parietal lobule and supramarginal gyrus, which are considered to be critical for working memory performance in both visual and auditory/phonological modalities (Koenigs, Barbey, Postle, & Grafman, 2009; Wager & Smith, 2003) and for phonological storage (Paulesu, Frith, & Frackowiak, 1993), respectively. Thus, the increased L-SPL/SMG activation may reflect increased cognitive loads on phonological processing for reading in L2 English, the less dominant language, in the J1/E2 group.

As shown in the brain-behavior relationships, in the English-L2 group (J1/E2 group), stronger L-SPL/SMG activation was associated with faster/more fluent reading of English words and greater phonological short-term memory capacity. This result may indicate that the J1/E2 readers accommodated to the additional phonological demands of irregular L2 English orthography and relied on phonological short-term memory for achieving L2 reading. In contrast, the E1/J2 group showed the opposite trend (albeit statistically non-significant) in the relationship between L-SPL/
SMG activation and phonological short-term memory (i.e., the stronger the L-SPL/SMG activation, the lower the phonological short-term memory). This observation is consistent with Prat, Keller, & Just (2007), in which high-capacity readers were more efficient, defined by the combination of higher performance and lower frontal and occipital activation. Therefore, the pattern of cerebral efficiency in the J1/E2 readers, at least in regions involved in phonological processing, may be different from the E1/J2 readers, presumably because L2 reading in English requires learners whose L1 has a regular orthography to accommodate to greater phonological demands inherent in irregular English orthography.

The L-SPL/SMG activation was greater in the J1/E2 group than the E1/J2 group only for the English word condition, but not for the Kana word condition. When comparing its activation within each group, for the J1/E2 group the L-SPL/SMG’s activation was greater for their L2 English words than their L1 Kana words. This is consistent with a previous fMRI result in Japanese skilled readers who learnt English as L2 (Buchweitz, Mason, Hasegawa, & Just, 2009). However, in the E1/J2 group, the L1–L2 difference in L-SPL/SMG activation was not statistically significant, yet it appears that L-SPL/SMG was more strongly activated for L2 Kana words than L1 English words (note: there was a non-statistically significant trend in this group). These results from both L2 groups suggest that the less dominant language (L2s in both groups) is generally more phonological demanding, but the additional L-SPL/SMG activation required for L2 reading is higher particularly when an L2 writing system requires readers to accommodate to higher phonological demands relative to their L1 writing system.

Given that the observed L2 group effect on L-SPL/SMG reflects greater requirement for integrating orthographic and phonological representations in English words in readers with regular L1 orthography, a lesser level of phonological demands may have been required for L2 Kana words in the E1/J2 group (this explaining why there is no observed L2 group effect in L-SPL/SMG during the Kana word condition). This is because E1/J2 readers’ phonological skills, which enable reading in irregular English orthography, may be sufficient enough to read words in regular orthographies. This interpretation is consistent with the psycholinguistic grain size theory of reading development, which proposes that different grain sizes of orthographic representations (fine-grained exemplified by English, coarse-grained exemplified by Spanish and Finnish) result in the development of different reading strategies (Ziegler & Goswami, 2005).

4.2. The L2 group effect for Kana words

The L2 group effect during the Kana word condition was seen in the lingual gyrus in both the left and right hemispheres (L-LG/LOC and R-LG). When looking at within-group activation in these clusters, both L-LG/LOC and R-LG exhibited greater activation for L2 Kana reading than L1 English reading within the E1/J2 group, but such a L1–L2 difference was absent in the J1/L2 group. The activation of each L-LG/LOC and R-LG for Kana words was associated with higher visual short-term memory skills in the E1/J2 group, indicating greater visual processing involved in Kana reading in this group. However, a greater involvement of LG functions may not necessarily be efficient for L2 reading, given that stronger LG activation was associated with slower or less fluent reading of Kana words in the E1/J2 group.
This brain-behavior relationship is consistent with Uta Frith’s three-stage theory of word recognition (1985), proposing that reading beginners (i.e., less skilled readers) recognize symbols and words visually (i.e., the logographic stage) before shifting to more efficient stages (e.g., the orthographic stage where grapheme-phoneme correspondence plays a key role). Although the E1/J2 readers in the current study were neither reading beginners nor performing worse than the J1/E2 readers (i.e. no group difference in accuracy) during the task inside the scanner, they were undoubtedly less fluent readers of Kana words than the J1/E2 readers, as evidenced by their longer response times for Kana word reading outside the scanner.

In the fMRI literature, the lingual gyrus is not considered as a core region involved in visual short-term memory (Christophel, Hebart, & Haynes, 2012; Haxby, Petit, Ungerleider, & Courtney, 2000; see review by Smith & Jonides, 1997), but is often activated by visual short-term memory tasks, particularly those involving maintenance (Harrison & Tong, 2009; Konstantinou, Brahrami, Rees, & Lavie, 2012; Sneve, Alnaes, Endestad, Greenlee, & Magnussen, 2012). During word reading, the lingual gyrus is believed to be specifically responsive to the physical length of stimuli (i.e., letter-strings) (Indefrey et al. 1997; Mechelli, Humphreys, Mayall, Olson, & Price, 2000), and to visual familiarity (i.e., greater activation for false fonts than words) (Tagamets, Novick, Chalmers, & Friedman, 2000). Given that visual word length was matched between Kana and English words in the current study, it is likely that the stronger LG activation reflects the greater visual processing demands associated with the lower visual familiarity with Kana words in the E1/J2 group.

This assumption, focusing on a close relationship between LG activation and visual familiarity, is supported by the secondary analysis (Supplementary Fig. 2). In the E1/J2 group, the L-LG/LOC activation for the visually unfamiliar and unpronounceable Tibetan strings was higher only relative to their L1 English words (not relative to their L2 Kana words). In contrast, the J1/E2 group exhibited significantly greater L-LG activation for Tibetan letter strings relative to both their L1 Kana and L2 English words. These results led us to interpret that visual features of Kana symbols may remain unfamiliar (or may not become entirely familiar) to the E1/J2 group.

If our interpretation is true enough to result in the increased LG activation in the E1/J2 group, an obvious question arising here is why this L2 group effect on LG was present only in the E1/J2 group but not in the J1/E2 group. A possible answer is due to the unequal level of visual exposure to L2 symbols between the two groups. Kana symbols, visually distinct from the Roman alphabets used in English orthography (Fig. 1), are unique to Japanese orthography and thus rarely seen outside Japan. In contrast, Roman alphabetic symbols are widely used, and indeed are seen everywhere in Japan (e.g. in commercial logos, advertising, videos and across the world wide web). Hence, the level of visual familiarity to L2 symbols may be much stronger in the J1/E2 group (i.e. Roman alphabets in L2) than the E1/J2 group (i.e. Kana symbols in L2).

However, it should be emphasized here that mere visual perception of Roman alphabets is unlikely to enable children to systematically learn how to phonologically decode words, particularly in irregular English orthography (Manolitsis, Georgiou, Stephenson, & Parrilla, 2009). Instead, it is more likely that earlier visual exposure to Roman alphabets in the J1/E2 group increases the visual familiarity of Roman alphabetic symbols/words, which may facilitate visual word recognition when they read L2 English words (i.e., strings of alphabetic symbols/letters). Further research is required to determine if L2 readers of Japanese with early exposure to Kana symbols, unlike our participants who started learning to read Kana during adolescence, show attenuated LG activation during Kana word reading. This would further clarify the role of the LG in L2 word reading, particularly considering that both groups, even the E1/J2 group (which showed the L2 group effect for Kana), exhibited low/non-statistically significant LG activation for both word conditions.

5. Conclusion and educational implications

We demonstrate here for the first time that cerebral correlates of increased cognitive loads to achieve L2 reading are dependent upon linguistic differences between L1 and L2, and that different brain regions play an important role in L2 reading in different writing systems, at least in late L2 readers. In other words, L2 reading depends both on which language is the learners’ L1 and which language is to be learnt as their L2. Late L2 readers of English, whose L1 writing systems have a more regular orthography (e.g. Japanese Kana, Italian, Spanish), may need to meet the greater phonological demands of the irregular orthography inherent in English. This suggests that reading programs designed for improving phonological and orthographic skills in English reading (e.g. Orton Gillingham, www.ortonacademy.org) can be effective for the majority of late L2 readers of English, considering that many writing systems have more regular orthographies than English. In contrast, late L2 readers of Japanese, whose L1 uses the Roman alphabet, need to adapt to the greater visual demands of L2 symbols. For these late L2 learners (e.g. learning Kana, Arabic), familiarization with the visual features of the L2 symbols is an important initial step. Consequently, language programs that place a heavy early emphasis on accurate visual recognition ought to be more effective in the long run. Overall, successful teaching of L2 reading, particularly for late adult learners, should take into account the important differences between L1 and L2 scripts.

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Appendix A. Supporting information

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References


