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Neuroimaging studies of reading in bilinguals*

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The ability to learn a second language is a skill that is often mediated by functional and structural changes in the brain. An inverted U-shaped function has been revealed in the neural response with increased expertise of L2 reading. In particular, the neural response at the left temporo-occipital region increases after initial learning and then decreases with increased expertise and efficiency. Another intriguing question in the literature of bilingual reading is whether brain activation for L2 is similar to or different from that for L1, which seems to be driven by tangled variables such as the proficiency level of L2, age of acquisition in L2, and orthographic transparency of L2 in relation to L1. In addition, the established L1 reading mechanisms and skills constrain how L2 is being learned in the brain, while acquiring a L2 also reversely influences how L1 is processed in the brain.

Keywords: fMRI, reading, bilingual, neuroimaging

Reading is a complex cognitive process that includes visual analysis of print, recognition of word form, and conversion from orthography to phonology and meaning. This process of reading is universal across different languages with accommodation to special features of each language at each level of the process (Perfetti & Liu, 2005). Neuroimaging studies have identified a neural circuit involved in reading which includes left temporo-occipital regions for visual-orthographic recognition, left inferior parietal lobule for conversion from orthography to phonology and semantics, left superior temporal gyrus for phonological representation, left middle temporal gyrus for semantic representation, and left inferior frontal gyrus for semantic, syntactic and phonological processing (Pugh, Shaywitz, Shaywitz, Constable, Skudlarski, Fulbright, Bronen, Shankweiler, Katz, Fletcher & Gore, 1996; Fiez & Petersen, 1998; Booth, Burman, Meyer, Gitelman, Parrish & Mesulam, 2002) (Figure 1). Learning to read in a second language follows the same cognitive processes and therefore provides a great model to study the process of reading acquisition in the brain (Xue, Mei, Chen, Lu, Poldrack & Dong, 2010). The neural network of reading shows an inverted U-shaped function with the acquisition of expertise in the second language reading (Price, 2013). The rising part of the inverted U is illustrated by studies showing that learning to read is related to increased activation in the left temporo-occipital regions including the visual-word-form-area, irrespective of whether learning is focused on lexical or sublexical strategies (Mei, Xue, Lu, He, Zhang, Xue, Chen & Dong, 2013; Pugh, Landi, Preston, Mencl, Austin, Sibley, Fulbright, Seidenberg, Grigorenko, Constable, Molfese & Frost, 2013), suggesting this region is more sensitive to the new script after initial learning during which meaning and phonology are attached to it. The falling part of the inverted U is illustrated by studies showing that activation in the left temporo-occipital regions decreases with the familiarity of the script (Twomey, Kawabata Duncan, Hogan, Morita, Umeda, Sakai & Devlin, 2013) and studies that show reduced activation in other parts of the reading network. A study that looked at the acquisition of literacy in a group of adults who were illiterate in their first acquired language but literate in their second language – which was German – (Abutalebi, Keim, Brambati, Tettamanti, Cappa, De Bleser & Perani, 2007) has found that with learning of the orthography of their first language, there is reduced activation in left middle, inferior frontal gyrus, left superior temporal gyrus, left precuneus, left inferior parietal lobule and left inferior fusiform gyrus. Thus, the buildup of a new orthographic lexicon may be achieved through the interplay of these brain areas that sub-serve different aspects of reading and reading acquisition. Another training study found that learning to read Chinese in a group of English speakers is related with reduced brain activation in left superior parietal lobule, left fusiform gyrus and left inferior frontal gyrus (Deng, Booth, Chou, Ding & Peng, 2008). Taken together, training studies suggest that there is an inverted U-shaped function in the reading network with increased expertise in second language reading; however a longitudinal study that can capture the complete learning curve in the brain is still much needed.

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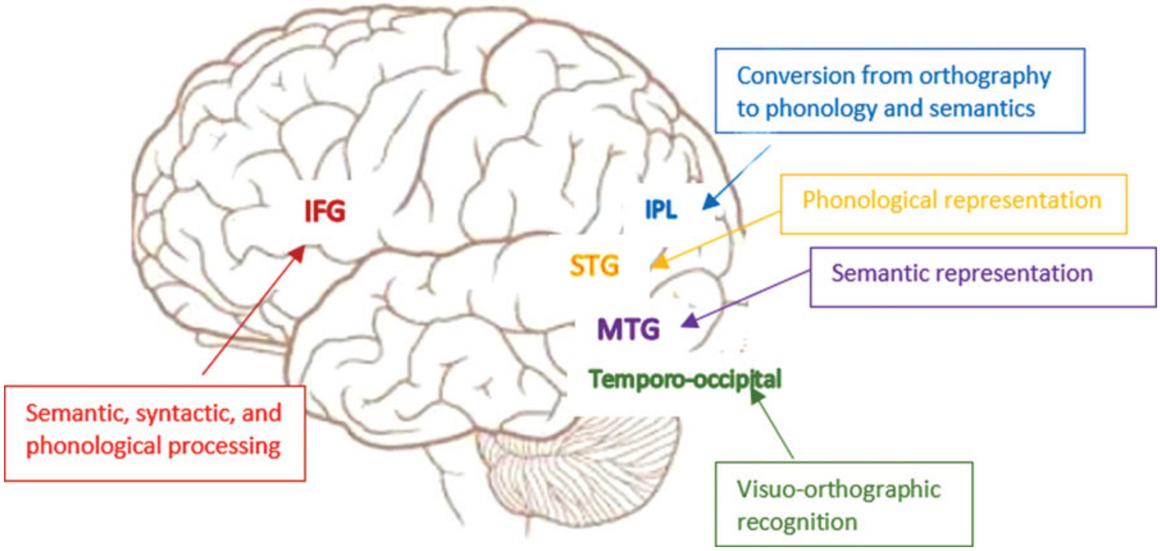

Figure 1. (Colour online) Demonstration of important regions in the reading network.

Orthographic transparency influences brain activation in L2 reading

Over and above the inverted U-shaped learning function, brain activation also varies with the reading strategy adopted. According to dual route models of reading, single words can be read in two distinct ways: a direct 'lexical' route and an indirect 'sublexical' route (Coltheart, Curtis, Atkins & Haller, 1993). Orthographic differences across languages impose differential weighting on distinct component processes, and consequently on different routes/pathways during word-reading tasks (Coltheart & Crain, 2012). The dorsal pathway including the left temporo-parietal region is engaged in the sublexical route while the ventral pathway including the left fusiform gyrus and left inferior frontal gyrus is engaged in the lexical route (Paulesu, McCrory, Fazio, Menoncello, Brunswick, Cappa, Cotelli, Cossu, Corte, Lorusso, Pesenti, Gallagher, Perani, Price, Frith & Frith, 2000; Bolger, Hornickel, Cone, Burman & Booth, 2008; Zhang, Chen, Xue, Lu, Mei, Xue, Wei, He, Li & Dong, 2014). Readers of transparent orthographies such as Italian and Hindi are thought to rely on spelling-to-sound assembly and show increased activation in phonologically tuned areas along the dorsal pathway including the left temporo-parietal region (Paulesu et al., 2000, Sakurai, Momose, Iwata, Sudo, Ohtomo & Kanazawa, 2000), whereas reading an opaque orthography such as English is thought to rely more on lexically mediated processing associated with increased activation of semantically tuned regions along the ventral pathway including the left fusiform gyrus and inferior frontal gyrus (Tokunaga, Nishikawa, Ikejiri, Nakagawa, Yasuno, Hashikawa, Nishimura, Sugita & Takeda, 1999; Paulesu et al., 2000; Chen, Fu, Iversen, Smith & Matthews, 2002; Chen, Vaid, Bortfeld & Boas, 2008).

Bilingual studies have demonstrated the distinct pathways corresponding to different orthographic transparency in a within-subject manner (Cherodath & Singh, 2015). For example, quite a few studies have found that left middle/inferior frontal gyrus and left fusiform gyrus are more involved in the more opaque language in a bilingual context, greater for Chinese than for English in English–Chinese bilinguals (Nelson, Liu, Fiez & Perfetti, 2009), greater for Urdu than for Hindi in Urdu–Hindi equal bilinguals (Kumar, 2014), greater for English than for Spanish in Spanish–English equal bilinguals (Jamal, Piche, Napoliello, Perfetti & Eden, 2012), greater for English than French in French–English bilinguals (Berken, Gracco, Chen, Watkins, Baum, Callahan & Klein, 2015), and greater for English than for Hindi in English–Hindi bilinguals (Das, Padakannaya, Pugh & Singh, 2011). In contrast, the dorsal pathway including the left temporo-parietal regions is more involved in the more transparent language: greater for Spanish than for English in Spanish–English equal bilinguals (Jamal et al., 2012), greater for German than for French in French–German bilinguals (Buetler, de Leon Rodriguez, Laganaro, Muri, Spierer & Annoni, 2014), and greater for Hindi than for English in English–Hindi bilinguals (Das et al., 2011). Taken together, orthographic transparency plays an important role in determining brain activation during word reading in both L1 and L2.

In the bilingual situation, however, whether the transparent language is acquired first or the opaque language is acquired first also makes a difference in brain activation of L2. When L1 is more opaque, for example, in Chinese–English bilinguals, English reading

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evokes a network which is identical to Chinese reading (Chee, Caplan, Soon, Sriram, Tan, Thiel & Weekes, 1999; Tan, Spinks, Feng, Siok, Perfetti, Xiong, Fox, Gao & Kalogirou, 2003; Cao, Tao, Liu, Perfetti & Booth, 2013), suggesting that the existing mechanisms are sufficient for the new L2. When L1 is more transparent than L2, for example, in English–Chinese bilinguals, significant accommodations were observed including greater involvement of the left middle frontal gyrus and the right fusiform gyrus for Chinese than English reading (Liu, Dunlap, Fiez & Perfetti, 2007; Nelson et al., 2009), suggesting that additional neural resources are required for the new L2. One possible explanation is that when L2 is more transparent than L1 (i.e., in Chinese–English bilinguals), the existing L1 system is sophisticated enough for the more regular mapping in L2; while when L2 is more opaque than L1 (i.e., in English–Chinese bilinguals), additional new mechanisms are required in order to deal with the arbitrary mapping between orthographic and phonology in L2. Future research needs to test this hypothesis by comparing two bilingual groups with the same L2 but different L1. In one group, L2 is more opaque than L1 and in the other group, L2 is more transparent than L1, such as Chinese–English and Spanish–English bilinguals.

Proficiency effect in the bilingual brain

Proficiency is another intriguing factor that influences brain activation in the bilingual brain. General proficiency effects have been reported that L2 reading is related with an extended network than L1 reading including but not limited to the left prefrontal cortex and anterior cingulate cortex, because of the lower proficiency in L2 than in L1 (Stowe & Sabourin, 2005, Indefrey, 2006, Abutalebi, 2008, Sebastian, 2011). However, even when proficiency is matched, there seems to be greater activation in the attention network for L2 than L1. For example, Kovelman and colleagues showed that bilateral dorsal lateral prefrontal cortex and inferior frontal cortex are more involved in bilinguals than in monolinguals in English semantic processing (Kovelman, Shalinsky, Berens & Petitto, 2008) and English syntactic processing (Kovelman, Baker & Petitto, 2008) when comparing early Spanish–English bilinguals to English monolinguals with matched proficiency on English. Taken together, one fundamental difference between L1 processing and L2 processing is the greater involvement of the attentional control network in L2 which is not completely explainable by proficiency.

Studies have also examined whether Higher L2 proficiency is related with greater similarity to L1 or greater accommodation to L2. There has been evidence that higher proficiency in the second language is related with greater similarity to brain activation in the first language during semantic judgment in a group of English–German bilinguals (Stein, Federspiel, Koenig, Wirth, Lehmann, Wiest, Strik, Brandeis & Dierks, 2009), and during visual word rhyming judgment in a group of late Chinese–English bilinguals (Cao et al., 2013). In contrast, there are also studies that have found higher proficiency in the second language is related with greater accommodation to L2. Studies found that in late English–Chinese bilinguals, high proficiency in L2, Chinese was associated with increased brain activation in two 'Chinese' regions, right superior parietal lobule and right lingual gyrus in a lexical decision task (Cao, Vu, Chan, Lawrence, Harris, Guan, Xu & Perfetti, 2013). In another 'Chinese' region (i.e., left superior parietal lobule), there was increased activation with greater proficiency improvement from early learning to late learning in a meaning match judgment task (Deng et al., 2008). The three 'Chinese' regions from the two studies mentioned above are found to be more involved in Chinese L1 readers than in English L1 readers (Bolger, Perfetti & Schneider, 2005; Tan, Laird, Karl & Fox, 2005), suggesting that higher proficiency in L2 is related with greater accommodation to the new language. In consistent, a recent study on late Chinese–English bilinguals has found that higher proficiency in L2 (i.e., English) is characterized by greater connectivity with the left supramarginal gyrus and left superior temporal gyrus (Cao, Kim, Liu & Liu, 2014). Both of these regions have been found to be more involved in English L1 readers than in Chinese L1 readers (Bolger et al., 2005; Tan et al., 2005; Cao, Brennan & Booth, 2015), presumably because this temporo-parietal region is involved in fine-grained mapping between orthography and phonology such as grapheme-phoneme-correspondence in reading (Bookheimer, Zeffiro, Blaxton, Gaillard & Theodore, 1995; Booth et al., 2002). In summary, previous studies have produced controversial findings about whether high proficiency in L2 is related with greater similarity to L1 or greater accommodation to L2.

AOA of L2 affects how L2 is processed in the brain

Another factor that determines brain activation in L2 processing is age of acquisition. Even when proficiency is matched in early and late bilinguals, brain activation for L2 varies according to the age of acquisition. One study found that early simultaneous bilinguals showed distinct activation for English and Hindi with greater activation in left inferior temporal gyrus for English and greater activation in left inferior parietal lobule for Hindi in a word reading task. However, late bilinguals with a comparable proficiency level to the early bilinguals activated similar network for both languages, suggesting greater accommodation in early bilinguals than in late bilinguals (Das et al., 2011). On the other hand, there is also well documented evidence that accommodation is more prominent in late bilinguals and assimilation is more prominent in early bilinguals. A study by Kim et al. (Kim, Relkin, Lee & Hirsch, 1997) found that late bilinguals showed distinct activation within the Broca's area, while early bilinguals showed an overlap between two languages in Broca's area in a silent internally expressive linguistic task (Kim et al., 1997). Another piece of evidence for greater assimilation in early bilingual and greater accommodation in late bilinguals comes from a sentence reading study, in which researchers found that for both grammatical and semantic processing, early bilinguals showed little or no distinction between L1 (i.e., Italian) and L2 (i.e., German), while late bilinguals showed greater involvement of left inferior frontal gyrus in L2 than in L1, even when their proficiency was comparable to the early bilinguals (Wartenburger, Heekeren, Abutalebi, Cappa, Villringer & Perani, 2003). Another study found increased activation in left IFG, left fusiform gyrus, left premotor cortex, orthography phonology mapping region, speech-motor regions in L2 reading aloud than L1 in sequential late French–English bilinguals, while early simultaneous bilinguals showed an overlapped network (Berken et al., 2015). While the studies mentioned above suggest controversial conclusions about how AOA influences assimilation and accommodation, there is also research that suggests AOA does not play a role in the pattern of assimilation and accommodation. By directly comparing early and late bilinguals, one study found that similar networks were involved in both groups for both L1 and L2, suggesting that for both early and late bilinguals, assimilation is dominant (Chee, Tan & Thiel, 1999; Yang, Tan & Li, 2011). Taken together, findings of how AOA influences assimilation and accommodation are not consistent.

L1 influences how L2 is being learned in the brain

The established L1 skills actually constrain what can be learned in L2 and how L2 can be learned (Li & Farkas, 2002). One fMRI study found supporting evidence for cross-linguistic influences of L1 on L2. In this study, it was found that native Chinese speakers showed greater activation in left middle frontal gyrus than native Korean speakers in reading Japanese kana, with matched AOA and proficiency in the two bilingual groups (Yokoyama, Kim, Uchida, Miyamoto, Yoshimoto & Kawashima, 2013). Left middle frontal gyrus has been found to be more involved in Chinese reading than other languages, probably due to the unique whole-character to whole-syllable mapping procedure in reading (Berken et al., 2015). The finding from Yokoyama et al.'s study suggests that the brain regions and cognitive strategies involved in reading a L2 is constrained by L1. In learning to read a second language, the properties of the L2 writing system and the distance between L1 and L2 also affects the learning process (Gleitman, 1985, Bassetti, 2008). Jeong et al. (Jeong, Sugiura, Sassa, Haji, Usui, Taira, Horie, Sato & Kawashima, 2007) found that native Korean speakers showed greater similarity to their native reading network when reading Japanese sentences than when reading English sentences. This was interpreted as a reflection of greater grammar similarity between Korean and Japanese than that between Korean and English. When the study was conducted among native Chinese speakers, however, it was found that there was greater similarity to native reading network when reading English sentences than reading Japanese sentences (Jeong, Sugiura, Sassa, Yokoyama, Horie, Sato, Taira & Kawashima, 2007). Again it is because Chinese and English grammar is more similar than Chinese and Japanese grammar. Therefore, a limited number of studies tend to suggest that short distance between L1 and L2 is associated with greater similarity and long distance is associated with greater accommodation.

Learning a second language changes how the first language is processed

Traditionally, researchers have not entertained the idea that one's native language is something subject to influence from the second language, but more recent evidence does suggests that L1 is more permeable than we thought, and is such that L2 to L1 influences not only exist for early simultaneous bilinguals, but also for late, successive bilinguals (Pavlenko & Malt, 2011). Very few neuroimaging studies have examined how L1 network changes after a second language is acquired. One study found that left ventral prefrontal activation for first language reading increases with second language vocabulary knowledge (Nosarti, Mechelli, Green & Price, 2009). One recent study also found greater activation in left inferior frontal gyrus, superior temporal gyrus, inferior parietal lobule and right homologues in bilinguals than monolinguals in reading regular, irregular, nonsense words in L1 (Jasinska & Petitto, 2014). It suggests that the experience of exposure to two phonological systems results in greater activation in the phonological processing regions in the brain. Another study found that long-term experience of Chinese is associated with increased involvement of the right fusiform gyrus in native English speakers, suggesting that L2 can modulate how L1 is processed at the visual-orthographic level as well (Mei, Xue, Lu, Chen, Wei, He & Dong, 2015). In summary, it suggests that knowing a second language fundamentally changes how the brain processes languages and that the greater activation in the language network and brain regions involved in monitoring and attention may be related with the enhanced linguistic competition and cognitive processing.

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