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Similarities and differences in brain activation and functional connectivity in first and second language reading: Evidence from Chinese learners of English

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ABSTRACT

It has been evidenced that both similarities and differences exist in the brain network involved in second language reading in comparison to the first language reading. However, very few studies have been done to compare functional connectivity in L1 and L2 reading. Brain activation and functional connectivity during English pseudoword rhyming judgment in a group of late Chinese–English bilinguals (the CE group) were compared to a Chinese word rhyming judgment task in another group of late Chinese–English bilinguals (the CC group). Brain activation analyses revealed that the two groups engaged a similar network and that the only significant group difference was greater involvement of the right middle occipital gyrus in the CC group than in the CE group, due to greater holistic visuospatial processing of Chinese characters. English pseudowords can be read using the same network as Chinese characters, whereas psychophysiological interaction (PPI) analyses revealed different connectivity within the reading network between the two groups. Greater functional connectivity was found between three visuo-orthographic seed regions and the right precentral gyrus in the CC group, suggesting that the sensorimotor patterns of Chinese syllables are activated during Chinese word rhyming judgment. In contrast, we found greater connectivity between the three seed regions and the left postcentral gyrus in the CE group. In addition, the connectivity between one of the three seed regions (i.e. the right middle occipital gyrus) and the left postcentral gyrus was positively correlated with English proficiency in the CE group. This suggests that somatosensory feedback plays a key role in processing the foreign phonemes of English pseudowords and those highly proficient bilinguals tend to rely on this information to a greater degree. We also found that within the CE group, the connectivity between the right middle occipital gyrus and the left inferior parietal lobule was positively correlated with accuracy, and that the connectivity between the right middle occipital gyrus and the left superior temporal gyrus was negatively correlated with reaction time. These results suggest that even if a Chinese network is used in reading English pseudowords, the classic grapheme–phoneme-correspondence regions that are important for native English reading are involved in highly performing bilinguals by connecting them with the visuo-orthographic region.

1. Introduction

It has been well documented that reading in both first and second languages is associated with a similar network in the brain, but with differences in certain regions (Hernandez, 2009; Meschyan & Hernandez, 2006; Nelson, Liu, Fiez, & Perfetti, 2009; Perani et al., 2003). This could be explained by the framework of assimilation and accommodation (Perfetti, Liu, & Tan, 2005; Piaget, 1983). Assimilation refers to using the procedures of the existing reading network in the acquisition of a new writing system, while accommodation refers to using new procedures for reading the new writing system (Perfetti et al., 2005; Piaget, 1983). Interestingly, it has consistently been found that the Chinese (L1) network

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is used in English (L2) processing in Chinese–English bilinguals, including early (Chee, Tan, & Thiel, 1999) and late bilinguals (Tan et al., 2003), bilingual children (Xue, Dong, Jin, Zhang, & Wang, 2004) and bilingual adults (Ding et al., 2003; Yang et al., 2011), as well as high and low proficiency bilinguals (Cao, Tao, Liu, Perfetti, & Booth, 2013). While the bilingual studies suggest that English words can be read using the Chinese network, monolingual studies suggest that English word reading involves a different network than Chinese word reading (Bolger, Perfetti, & Schneider, 2005; Tan, Laird, Karl, & Fox, 2005). English word reading is related to greater activation in the left posterior superior temporal gyrus (STG), the left inferior parietal lobule (IPL) and the left inferior frontal gyrus (IFG), all of which have been found to be associated with phonologic procedures in English. The left posterior superior temporal gyrus is associated with fine-grained phonological representation (Booth et al., 2003; Nakamura et al., 2006; Temple et al., 2003), the left inferior parietal lobule is associated with grapheme–phoneme-conversion (Booth et al., 2003; Paulesu et al., 2000), and the left inferior frontal gyrus is associated with phoneme manipulation and phonological rehearsal before speech production (Fiez, 1997; Price, 2010). In contrast, Chinese word reading is related to greater activation in the left middle frontal gyrus and the right middle occipital gyrus (Bolger et al., 2005; Tan et al., 2005). The left middle frontal gyrus has been found to be associated with the phonological procedures of character–syllable mapping in Chinese, and the right middle occipital gyrus has been found to be associated with the holistic visuospatial configuration of Chinese characters. The only accommodation that has been found in Chinese learners of English is at the visual form level: there is reduced involvement of the right middle occipital gyrus for reading English words than for reading Chinese words (Cao et al., 2013; Liu & Perfetti, 2003). Chinese–English bilingual studies have reported no accommodation at the English phonological regions (i.e. the left IFG and left STG) (Tan et al., 2003) and reduced accommodation at regions with higher proficiency (i.e. the left IFG) (Cao et al., 2013). However, there is a possibility that the English phonological regions may contribute when Chinese–English bilinguals read English words by connecting with other regions in the network. Functional connectivity studies need to be conducted in order to test this possibility.

Although studies have consistently suggested assimilation in Chinese–English bilinguals, a network could shift from one behavioral goal to another, not because of differences in the distribution of activations, but because of differences in the interactions among its components (Damasio, 1989; McIntosh, 2000; Mesulam, 1981, 1998). Therefore, it is important to examine functional connectivity in the network during both L1 and L2 reading. Unfortunately, there have only been two published studies that compared functional connectivity in L1 and L2, and they have produced controversial results. One Spanish–English bilingual study using effective connectivity analysis found that the visual word form area was connected directly to the left IFG in English word reading, while it was connected with the left angular gyrus, then to the left IFG in Spanish word reading. Additionally, the connection strength between the visual word form area and the angular gyrus is correlated with proficiency in Spanish (Boukrina, Hanson, & Hanson, 2014). Another study of late Chinese–English bilinguals found that the relationship between resting-state functional connectivity and reading ability does not differ in L1 and L2 (Zhang et al., 2014). This study found that, in both L1 and L2, highly efficient word reading is associated with greater connectivity between the left fusiform gyrus and bilateral motor areas (e.g. precentral gyrus, postcentral gyrus, and the supplementary motor area) and between the left superior temporal gyrus and the bilateral occipital cortex. The authors argue that the left fusiform gyrus and the bilateral occipital cortex are involved in visuo-orthographic processing, while the left superior temporal gyrus and bilateral motor areas are related to phonological processing. Therefore, their results suggest that the connectivity between phonological and orthographic regions increases with word reading efficiency in both L1 and L2. Another study using resting-state functional connectivity (Wang, Han, He, Liu, & Bi, 2012), however, suggests that the connectivity that is significantly correlated with reading competency in monolingual English speakers does not exhibit correlations with Chinese reading competency in Chinese speakers. Resting-state functional connectivity may not be the best method of comparing connectivity in L1 and L2, due to the limitation that activity and connectivity cannot be actually separated in the resting state (O'Reilly, Woolrich, Behrens, Smith, & Johansen-Berg, 2012).

The current study compared brain activation and functional connectivity during English pseudoword reading in a group of late Chinese–English bilinguals (CE group) with Chinese word reading in another group of late Chinese–English bilinguals (CC group). We chose to use psychophysiological interaction (PPI) analysis to examine functional connectivity, because the purpose of a PPI analysis is to determine which voxels in the brain increase their responses as the influence of a seed region of interest in a given context, such as during a particular behavioral task (O'Reilly et al., 2012). Our study is the first to directly compare functional connectivity in the brain in Chinese (L1) and English (L2) reading. Since reading is essentially the process of accessing meaning and phonology from orthography, we chose visuo-orthographic areas as our seed regions and examined which brain regions were connected with them. Based on the literature (Bolger et al., 2005; Tan et al., 2005), three visuo-orthographic seed regions were included in the current study, namely, the left fusiform gyrus (FG), the left middle occipital gyrus (MOG) and the right middle occipital gyrus (rMOG). We expected that functional connectivity analysis might have the ability to reveal differences between L1 and L2 reading, which cannot be detected in brain activation analysis. We also examined how proficiency and performance in L2 reading would modulate functional connectivity. We expected that high performance would be related to greater connectivity with the English phonological regions (i.e. left IFG, left STG, and left IPL) in the CE group. Another novelty of the current study is the use of English pseudowords, which creates the most contrastive writing system for Chinese. Chinese characters can only be read by character–syllable mapping, whereas English pseudowords can only be read by grapheme–phoneme-conversion. We expected that even English pseudowords would be read using the Chinese network in our bilingual subjects, even though we expected greater lexical semantic processing involved in Chinese character reading than in English pseudoword reading.

2. Methods

2.1. Participants

Two groups of Chinese undergraduate and graduate students were recruited from Beijing Normal University in Beijing, China. One group performed an English pseudoword rhyming judgment task (CE group) ($N=15$, mean age=22.9 years), and the other group performed a Chinese word rhyming judgment task (CC group) ($N=20$, mean age=21 years). Participants in both groups were late Chinese–English bilinguals; however only the CE group received an English proficiency tests. Participants in the CE group had an average age of English acquisition of 12 years (range: 9–13 years). Their English proficiency was assessed with five subtests in a standardized English reading test, Woodcock Johnson-III (Woodcock, McGrew, & Mather, 2001): vocabulary, Antonyms; vocabulary, Synonyms; word reading accuracy, Word ID; pseudoword reading accuracy, Word Attack; and reading speed, Reading Fluency (see Table 1). All participants were right-handed, free of any neurological disease or psychiatric disorders, did not suffer from attention deficit hyperactivity disorder and did not have any learning disabilities. The institutional review board at Beijing Normal University approved the informed consent procedures of the current study.