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Reading across writing systems: A meta-analysis of the neural correlates for first and second language reading

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Abstract

Numerous studies have investigated the neural correlates of reading in two languages. However, reliable conclusions have not been established as to the relationship of the neural correlates underlying reading in the first (L1) and second (L2) language. Here, we conduct meta-analyses to address this issue. We found that compared to L1, the left inferior parietal lobule showed greater activation during L2 processing across all bilingual studies. We then divided the literature into two categories: bilingual participants who learned two languages with different writing systems and bilinguals who learned two languages with similar writing systems. We found that language differences in the neural correlates of reading were generally modulated by writing system similarity, except the region of the left inferior parietal lobule, which showed preferences for L2 reading in both types of bilinguals. These findings provide new insights into the brain mechanisms underlying reading in bilinguals.

1. Introduction

The human brain has a remarkable capacity to learn more than one language. However, how neural circuits underlie reading in different languages remains inconclusive. Early evidence suggests that the first (L1) and second language (L2) reading share a same set of brain regions (see Perani & Abutalebi, 2005). Recently, emerging evidence shows that reading in L2 may recruit extra neural resources compared to reading in L1. For example, it was found that, besides the common neural correlates, reading in L1 and L2 also evoked divergent patterns of activity in broad regions in Chinese–English bilinguals (Xu, Baldauf, Chang, Desimone & Tan, 2017). It was also reported that the activity in the left caudate predicts achievement in reading skills only in the second language. In addition, a recent study suggested that structural deficits in the left supramarginal gyrus are associated with a reading impairment in L2 (English) irrespective of the reading ability of L1 (Chinese) (Li, Booth, Bélanger, Feng, Tian, Xie, Zhang, Gao, Ang, Yang, Liu, Meng & Ding, 2018). Another study identified several brain regions underlying the shared semantic representations between L1 and L2, including the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus, while some other brain regions support L2 semantic processing only, including the left postcentral gyrus, the right precentral gyrus, the right supramarginal gyrus, and the right cuneus (Van de Putte, De Baene, Brass & Duyck, 2017). Overall, these studies suggest that L2 reading may recruit neural resources that are not necessary for L1. However, variances of the results in these studies prevent researchers from achieving a reliable conclusion.

Meta-analysis represents a unique approach to address this issue. Compared to an original study, a meta-analysis combines findings from multiple interrelated studies to obtain a more consistent and reliable result (Wager, Lindquist & Kaplan, 2007, Eickhoff, Laird, Grefkes, Wang, Zilles & Fox, 2009). Several meta-analyses of bilingual language processing have been performed (Indefrey, 2006; Sebastian, Laird & Kiran, 2011; Liu & Cao, 2016). Brain activities across languages are influenced by language proficiency (Sebastian et al., 2011) and the age of acquisition of the second language (AoA of L2; Liu & Cao, 2016; Cargnelutti, Tomasino & Fabbro, 2019). For highly proficient or early bilinguals, L1 and L2 rely on more similar neural correlates. However, for less proficient or late bilinguals, second language processing involves more distributed areas than first language (Sebastian et al., 2011; Liu & Cao, 2016). Liu and Cao (2016) also investigated the effect of differences in orthographic depth across languages on the adaption of the brain to new languages, i.e., deeper orthography in L2 relative to L1 vs. shallower orthography in L2 relative to L1. They observed that shallower and deeper L2s were represented by different neural circuits. Recently, a meta-analysis compared L1 and L2 language network with a consideration of different cognitive processes and suggested that two languages share neural networks with few differences on the linguistic level (Sulpizio, Del Maschio, Fedeli & Abutalebi, 2020).

Although these meta-analytic studies have improved our understanding of bilingual language processing, they primarily focused on language comprehension and production rather than reading. A core process of reading is to retrieve the phonological and semantic information based on the orthographic information, and this process varies in different writing systems (Mei, Xue, Lu, Chen, Zhang, He, Wei & Dong, 2014a, Mei, Xue, Lu, He, Zhang, Wei, Xue, Chen & Dong, 2014b, Xia, Hancock & Hoeft, 2017). For example, for phonogram systems, such as English or Spanish, word forms correspond to phonemes or syllables (Nelson, Liu, Fiez & Perfetti, 2009). Reading requires those sounds to be decoded and assembled, which strongly relies on the temporoparietal junction (Mei et al., 2014b). In contrast, for morpho-syllabic languages (or morphogram systems), such as Chinese, a graphic unit corresponds to a spoken syllable that happens to be a morpheme, a meaning unit. Word recognition in Chinese relies on the middle frontal gyrus, to directly address phonological and semantic information (Siok, Niu, Jin, Perfetti & Tan, 2008, Mei, Xue, Lu, He, Wei, Zhang, Dong & Chen, 2015). It was hypothesized that similar languages might be more likely to rely on overlapping cortical areas than dissimilar languages (Hasegawa, Carpenter & Just, 2002; Cao, 2016; Kim, Liu & Cao, 2017). Therefore, in terms of reading, differences in writing systems might modulate the cortical representations of different languages in bilinguals.

In the current study, we aimed to compare the brain functional organization for reading in L1 and L2 with a consideration of the nature of L1 and L2 writing systems. We first reviewed previous bilingual studies focusing on reading and conducted meta-analyses to identify differences in brain activation patterns between L1 and L2. We then investigated whether these differences will be influenced by writing system similarity. To this end, we divided the literature into two categories, the literature on bilinguals speaking two languages with different writing systems, i.e., one morphogram language and one phonogram language, and the literature on bilinguals speaking two languages with similar writing systems, i.e., both L1 and L2 are phonogram languages. Meta-analyses of L1 and L2 processing were conducted in each category.

2. Materials and methods

2.1 Meta-analyses of the topographic relationship between L1 and L2 in all bilinguals

Literature selection

Studies published before 2020 were retrieved through the database Google Scholar, with the keywords ("bilinguals") and ("reading") and ("imaging") and ("second language") and ("phonological processing" or "orthographic processing" or "semantic processing"). For meta-analyses, the following additional inclusion criteria were used: (1) Functional magnetic resonance imaging and Positron Emission Tomography (fMRI or PET) studies with complete coordinates of activation foci either in Talairach (Talairach & Tournoux, 1988) or Montreal Neurological Institute (MNI; Collins, Zijdenbos, Kollokian, Sled, Kabani, Holmes & Evans, 1998) space; (2) visually presented reading or reading-related tasks were employed, such as phonological, orthographic or semantic judgment; and (3) activation coordinates of typically developing readers were reported. We excluded the studies with the following characteristics: (1) performing electrophysiological recordings such as EEG or MEG instead of fMRI; (2) focusing on other types of processing, such as language production, language switching, or verb generation, rather than reading; (3) not including of typically developing readers; (4) presenting auditory stimuli.

Finally, 40 studies were selected (Table 1), and we initially conducted a meta-analysis of all 40 studies to identify differences in brain activation patterns between languages. Notably, for studies recruiting participants with various reading levels, peaks were only extracted from groups without dyslexia.

Meta-analyses based on GingerALE

Meta-analyses were conducted by calculating the activation likelihood estimation (ALE, Turkeltaub, Eickhoff, Laird, Fox, Wiener & Fox, 2012, Fox, Laird, Eickhoff, Lancaster, Fox, Uecker & Ray, 2013) using GingerALE (version 2.3.6, available at www.brainmap.org/ale). Prior to the meta-analyses, all Talairach coordinates were converted to MNI coordinates using the tal2icbm transformation (Lancaster, Tordesillas-Gutiérrez, Martinez, Salinas, Evans, Zilles, Mazziotta & Fox, 2007).

First, we performed separate ALE analyses of L1 and L2 in all bilinguals. L1 processing included 427 activation peak foci, and L2 processing included 500 activation peak foci. Both individual meta-analyses were corrected for multiple comparisons (voxel level $p < 0.001$, cluster level FWE-corrected to $p < 0.05$; Eickhoff, Nichols, Laird, Hoffstaedter, Amunts, Fox, Bzdok & Eickhoff, 2016; Eickhoff, Laird, Fox, Lancaster & Fox, 2017; Xu, Larsen, Baller, Scott, Sharma, Adebimpe, Basbaum, Dworkin, Edwards & Woolf, 2020).

Second, we compared the meta-map of L1 with that of L2 to investigate the specific neural representations of L1 and L2. We used permutation tests, during which all foci associated with L1 and L2 were pooled and were randomly divided into two groups each with the same sample size as the original datasets, to estimate the significance of the language differences. Meta-analyses were conducted based on the foci identified in each group. Subsequently, the difference in ALE scores of each voxel between these two groups was calculated. By repeating these processes 10,000 times, a null distribution of the difference in the ALE score for each voxel was obtained. This distribution allowed us to estimate the significance of language differences in each voxel. The significance of the "true" difference in the ALE score between L1 and L2 was then tested for each voxel based on the corresponding null distribution. An uncorrected threshold at a voxel-level $p < 0.05$ with a minimum cluster volume of 100 mm3 (Zmigrod, Garrison, Carr & Simons, 2016; Liang & Du, 2018) was used. All thresholded ALE maps were overlaid onto the Brainmesh_ICBM152.nv surf template in the BrainNet Viewer software (Xia, Wang & He, 2013; available at www.nitrc.org/projects/bnv/) and MRIcron software (available at www.nitrc.org/projects/mricron) for display.

2.2 Meta-analysis of the topographic relationship between L1 and L2 in different bilinguals

Languages learned by the bilinguals collected in the current study were either from morphogram systems or from phonogram writing systems. Morphogram systems included Chinese and Japanese Kanji, wherein a graphic symbol corresponds to a meaningful unit. Phonogram systems consisted of three sub-systems, alphabetic writing system, syllabary writing system, and alpha-syllabic writing system. Alphabetic writing systems include English, German, Italian, Portuguese, Spanish, Macedonian, which maps

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Table 1. A summary of studies focusing on two types of bilinguals.

Study	N (male/ female)	Mean Age (age range, years)	Language (L1)	Language (L2)	Task	Baseline	No. of foci (L1)	No. of foci (L2)
Bilinguals learning two languages with different writing systems (MP bilinguals)								
Buchweitz, Mason, Hasegawa and Just (2009)	9 (~)	27.4 (24–38)	Japanese (Kanji)	English	Sentence comprehension task	Fixation	0	15
Cao, Tao, Liu, Perfetti and Booth (2013)	26 (13/13)	22 (19–27)	Chinese	English	Rhyme judgment	Fixation	10	10
Cao and Perfetti (2016)	17 (4/13)	24.9 (19–29)	English	Chinese	Passive viewing task	Fixation	6	9
Chan, Luke, Li, Yip, Li, Weekes and Tan (2008)	11 (~)	~ (21–32)	Chinese	English	Noun/verb lexical decision task	Fixation	37	27
Chee, Hon, Lee and Soon (2001)	9 (5/4)	~ (23–34)	Chinese	English	Pyramids and palm trees semantic relatedness judgment	Font size decision task	4	6
Chee, Tan and Thiel (1999)	24 (8/16)	~ (~)	Chinese	English	Silently completed word stems	Fixation	1	1
Chee, Hon, Lee and Soon (2001)	10 (6/4)	~ (19–29)	English	Chinese	Pyramids and palm trees semantic relatedness judgment	Font size decision task	5	5
Ding, Perry, Peng, Ma, Li, Xu, Luo, Xu and Yang (2003)	6 (3/3)	23 (21–24)	Chinese	English	Orthographic search task/ semantic categorization task	Viewed the asterisk passively	13	14
Gao, Wei, Wang, Jian, Ding, Meng and Liu (2015)	28 (10/18)	9.9 (8.3–11.1)	Chinese	English	Rhyme judgment	Viewed the asterisk passively	28	27
Kim, Liu and Cao (2017)	17 (~)	22.8 (~)	Chinese	English	Rhyme judgment	Fixation	12	12
Li, Li, Yang, Guo and Wu (2014)	15 (8/7)	24.9 (20–35)	Japanese (Kanji)	English	Synonym judgments	Font size decision task	14	10
Liu, Dunlap, Fiez and Perfetti (2007)	29 (~)	~ (~)	English	Chinese	Passive viewing task	Fixation	14	16
Luke, Liu, Wai, Wan and Tan (2002)	7 (7/0)	~ (20–31)	Chinese	English	Semantic plausibility judgment task	Font size decision task	23	23
Ng (2008)	8 (4/4)	27(~)	Chinese	English	Word passive viewing	Checkerboard	2	1
Ng (2008)	8 (6/2)	33 (~)	English	Chinese	Word passive viewing	Checkerboard	1	2
Tan, Spinks, Feng, Siok, Perfetti, Xiong, Fox and Gao (2003)	12 (~)	~ (29–39)	Chinese	English	Rhyme judgment	Font size decision tasks	6	6
Tan, Rajapakse, Hong, Lee and Sitoh (2004)	6 (3/3)	~ (~)	Chinese	English	Silent word reading	View randomized Chinese words	15	13
	6 (3/3)	~ (18–23)	Chinese	English		Fixation	14	11

(*Continued*)

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Table 1. (*Continued.*)

Study	N (male/ female)	Mean Age (age range, years)	Language (L1)	Language (L2)	Task	Baseline	No. of foci (L1)	No. of foci (L2)
Tham, Liow, Rajapakse, Leong, Ng, Lim and Ho (2005)					Homophone matching task			
Tian, Li, Chu and Ding (2020)	20 (10/10)	22 (~)	Chinese	English	Real word reading	Fixation	6	6
Wang, Wang and Lee (2010)	12 (~/~)	~ (21–26)	Chinese	English	Silent word reading	Fixation	27	40
Xue, Dong, Jin, Zhang and Wang (2004)	12 (6/6)	11.6 (12–12)	Chinese	English	Semantic decision tasks	Fixation	18	18
Zhao, Li, Wang, Yang, Deng and Bi (2012)	20 (8/12)	23 (19–30)	English	Chinese	Pronounce the target characters covertly.	Fixation	0	7
Bilinguals learning two languages with similar writing systems (PP bilinguals)								
Buchweitz, Mason, Hasegawa and Just (2009)	9 (~)	27.4 (24–38)	Japanese (Kana)	English	Sentence comprehension task	Fixation	0	16
Buchweitz, Shinkareva, Mason, Mitchell and Just (2012)	11 (8/3)	29.9 (20–40)	Portuguese	English	Categorization of nouns related to dwellings/ tools	Fixation	25	26
Cao, Sussman, Rios, Yan, Wang, Spray and Mack (2017)	17 (2/15)	19.47 (18–22.3)	English	Spanish	Sound judgment task	Fixation	0	1
Das, Padakannaya, Pugh and Singh (2011)	14 (~)	~ (~)	Hindi	English	Word reading	Fixation	6	6
Das et al. (2011)	10 (~)	~ (~)	Hindi	English	Word reading	Fixation	1	10
Golestani, Alario, Meriaux, Le Bihan, Dehaene and Pallier (2006)	12 (7/5)	~ (20–28)	French	English	Covert word reading	Silence	5	6
Hernandez, Woods and Bradley (2015)	20 (~)	21.55 (18–26)	Spanish	English	Visual lexical processing task	Fixation	4	6
Hernandez et al. (2015)	21 (~)	10.52 (8–13)	Spanish	English	Visual lexical processing task	Fixation	2	4
Jamal, Piche, Napoliello, Perfetti and Eden (2012)	12 (7/5)	22.3 (20–25)	Spanish	English	Ascender letter detecting: real word	Pseudofonts	2	4
Kim, Liu and Cao (2017)	16 (~)	21.9 (~)	Korean	English	Rhyme judgment	Fixation	12	10
Koyama, Stein, Stoodley and Hansen (2013)	15 (4/11)	29.3 (~)	Japanese (Kana)	English	Phonological one-back matching task	Tibetan letter strings	9	9
Koyama et al. (2013)	14 (4/10)	26.2 (~)	English	Japanese (Kana)	Phonological one-back matching task	Tibetan letter strings	9	9
Kumar, Das, Bapi, Padakannaya, Joshi and Singh (2010)	12 (7/5)	28.4 (25–32)	Hindi	English	Covert reading of phrases	Fixation	9	8

(*Continued*)

Table 1. (*Continued.*)

Study	N (male/ female)	Mean Age (age range, years)	Language (L1)	Language (L2)	Task	Baseline	No. of foci (L1)	No. of foci (L2)
Meschyan and Hernandez (2006)	12 (8/4)	23 (18–29)	Spanish	English	Read words silently	Rest	12	6
Park, Badzakova-Trajkov and Waldie (2012)	8 (4/4)	25 (~)	Macedonian	English	Lexical decision/ letter case judgment	Fixation	0	4
Rao, Mathur and Singh (2013)	15 (9/6)	~ (18–27)	Hindi	English	Concrete noun judgment	Rest	40	38
Stein, Federspiel, Koenig, Wirth, Lehmann, Wiest, Strik, Brandeis and Dierks (2009)	10 (4/6)	17 (16–18)	English	German	Judgment of the meaning of known nouns	Fixation	23	50
Suh, Yoon, Lee, Chung, Cho and Park (2007)	16 (14/2)	22.9 (19–29)	Korean	English	Sentence comprehension task	Rest	12	8

Note. N: number of subjects. ~ indicates that the relevant information was not reported.

grapheme to phoneme. Syllabary writing system indicates Japanese Kana, with graphic units corresponding to syllabary. Hindi belongs to alpha-syllabic writing systems, which has the properties of both alphabetic and syllabary writing system. Each consonant in Hindi has an inherent associated vowel, which is different from purely alphabetic scripts. On the other hand, distinct syllables in Hindi were not represented by unique symbols, which differs from syllabic writing system (Das, Kumar, Bapi, Padakannaya & Singh, 2009).

We classified the bilingual literature into two categories to explore the effect of writing systems similarity. The first category consisted of 22 studies focusing on bilinguals speaking two languages with different writing systems: a morphogram writing system and a phonogram writing system (abbreviated to MP bilinguals, Table 1), i.e., Chinese–English bilinguals, English–Chinese bilinguals, and Japanese–English bilinguals reading Kanji or English. The second category consisted of 18 studies focusing on bilinguals speaking two languages with phonogram writing systems (abbreviated to PP bilinguals, Table 1). Then we conducted meta-analysis separately in MP bilinguals and PP bilinguals. For MP bilinguals, L1 processing included 256 activation peak foci, and L2 processing included 279 activation peak foci. For PP bilinguals, L1 processing included 171 activation peak foci, and L2 processing included 221 activation peak foci.

2.3 Meta-analysis of studies on Chinese–English bilinguals

Notably, previous studies on Chinese–English bilinguals generated complex profiles. For example, early evidence showed that reading in L2 (English) induces a very similar brain activation pattern as L1 (Chee, Caplan, Soon, Sriram, Tan, Thiel & Weekes, 1999, Illes, Francis, Desmond, Gabrieli, Glover, Poldrack, Lee & Wagner, 1999, Tan, Spinks, Feng, Siok, Perfetti, Xiong, Fox & Gao, 2003), suggesting that L2 reading might utilize the network of L1 (Chinese) (Tan et al., 2003). However, given that divergent neural activities might be more likely to be observed in bilinguals learning two different languages compared to bilinguals learning two similar languages, different neural correlates of reading across languages were supposed to be expected in Chinese–English bilinguals. To clarify this issue, we specifically focused on Chinese–English bilinguals. We extracted 15 studies on Chinese–English bilinguals and conducted meta-analyses similar to those described above.

3. Results

3.1 Cortical organizations of L1 and L2 reading in all bilinguals

For L1 processing, we observed six regions showing significant convergence across studies. The left precentral gyrus (BA6)/inferior frontal gyrus (BA46) was the largest cluster, followed by the left medial frontal gyrus/supplementary motor area (BA6) and the left precuneus (BA19). Other clusters included the left fusiform gyrus (BA18 and BA37) and the right inferior occipital gyrus/middle occipital gyrus (BA18, see Figure 1A). We also identified nine clusters involved in L2 processing. The largest cluster was located in the left middle frontal gyrus (BA9) extended to the inferior frontal gyrus, followed by the left precuneus (BA19), the left fusiform gyrus (BA37), the left medial frontal gyrus/supplementary motor area (BA6), and the right inferior occipital gyrus/middle occipital gyrus (BA18), largely overlapping with the pattern observed for L1. Other clusters consisted of the right fusiform gyrus (BA37), the right precuneus (BA7), the left insula (BA13), and the left fusiform gyrus (BA18, Table S1 and Figure 1A). Based on these results, the left inferior frontal gyrus, the left medial frontal gyrus/supplementary motor area, the left precuneus, the left fusiform gyrus, and the right middle occipital gyrus potentially represent the common neural profiles for L1 and L2.

We compared the ALE maps between L1 and L2 to further identify the language difference. The right fusiform gyrus (R.FFG, BA18) and the left middle frontal gyrus (L.MFG, BA9) showed consistent activation in response to reading L1. The left inferior parietal lobule (L.IPL, BA40), the right precuneus (R.PCUN, BA7), and the left insula (L.INS, BA13) showed consistent activation in response to reading L2 (Table 2 and Figure 1B).

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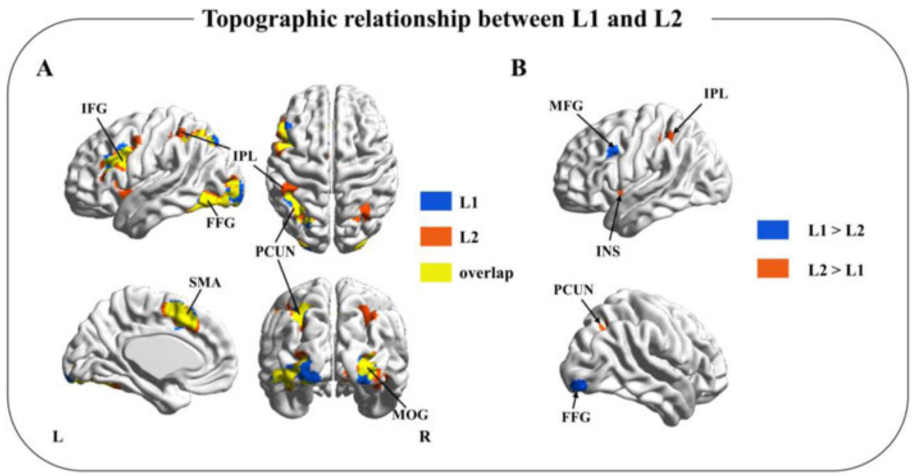

Fig. 1. (A) Brain regions showing consistent activation in response to reading L1 and L2 in all bilinguals (voxel height $p < 0.001$, cluster $p < 0.05$, FWE-corrected). The blue region represents the L1 meta-map, the orange region represents the L2 meta-map, and the yellow region represents the regions that overlapped in these two maps. (B) Brain regions that showed language differences in all bilinguals (uncorrected $p < 0.05$ with a minimum cluster volume of 100 mm3). Blue regions showed more consistent activation in response to L1 reading than L2 reading. Orange regions showed more consistent activation in response to L2 reading than L1 reading.
MFG = middle frontal gyrus, IFG = inferior frontal gyrus, IPL = inferior parietal lobule, SMA = supplementary motor area, MOG = middle occipital gyrus, FFG = fusiform gyrus, INS = insula, PCUN = precuneus.

3.2 Brain representation of L1 and L2 in the PP and MP bilinguals

We conducted separate meta-analyses of each type of bilingual to explore the effect of similarity in writing systems.

For bilinguals who learn two languages with greater differences in writing systems (MP bilinguals), meta-analyses of L1 and L2 were first conducted. We observed seven convergent regions in L1 processing and seven convergent regions in L2 processing (Table S2 and Figure 2A). By comparing the ALE maps between L1 and L2, we further observed that the left superior temporal gyrus (BA22), the left middle frontal gyrus (BA9), the left inferior frontal gyrus (BA45), and the right posterior fusiform gyrus (BA18) showed more consistent activation across studies of L1 processing in MP bilinguals compared to L2 processing. However, the left inferior parietal lobule (BA40) and the right anterior fusiform gyrus (BA37) showed more consistent activation during L2 processing compared to L1 processing (Table 2 and Figure 3A).

For bilinguals who learn two languages with similar writing systems (PP bilinguals), meta-analyses of L1 and L2 were also conducted. This analysis identified six convergent regions involved in L1 processing and seven convergent regions involved in L2 processing (Table S3 and Figure 2B). When comparing the two meta-maps, we did not observe any significant region showing more activation in L1 reading compared to L2 reading. However, the left middle frontal gyrus (BA46), the left inferior parietal lobule (BA40), and the left insula (BA13) showed more consistent activation in response to L2 reading than L1 reading (Table 2 and Figure 3B).

More importantly, the left inferior parietal lobule (L.IPL) identified in the comparison of MP bilinguals overlapped with the region identified in PP bilinguals (Figure 3C).

3.3 Additional analyses of Chinese–English bilinguals

We further examined the cortical representations of L1 and L2 in the Chinese–English bilinguals, and the results demonstrated six convergent regions involved in L1 processing and seven convergent regions involved in L2 processing (Table S4 and Figure S1). By comparing the two meta-maps, the left superior temporal gyrus (BA22), the left middle frontal gyrus (BA9), the left inferior frontal gyrus (BA45), and the right posterior fusiform gyrus (BA18) showed a more consistent activation in response to L1 than L2, whereas the left inferior parietal lobule and the right anterior fusiform gyrus (BA37) showed a more consistent activation in response to L2 than L1 (Table 2 and Figure 4). This result is consistent with our hypothesis that the brain might adapt to a new language by recruiting additional neural resources that are not necessary for L1, even in Chinese–English bilinguals.

4. Discussion

In the current study, we performed meta-analyses to examine the potential neural differences underlying L1 and L2 reading in bilinguals and investigated whether/how these differences were modulated by writing system similarity of two languages. We found that reading in L1 induced greater activation in the left middle frontal gyrus and the right posterior fusiform gyrus, whereas reading in L2 evoked more activation in the left inferior parietal lobule, the right precuneus, and the left insula. When dividing the bilinguals into two types, bilinguals learning two languages from morphogram and phonogram systems (MP bilinguals) and bilinguals learning two languages from phonogram systems (PP bilinguals), we further observed that language difference in the left inferior parietal lobule was found in both MP bilinguals and PP bilinguals, whereas brain organization in other four regions seems to be influenced by the similarity of writing systems. The current study reveals a relatively clear pattern about how one brain reads in two languages.

4.1 Greater involvement of the left inferior parietal lobule during reading in L2

Comparions between two languages showed that the left inferior parietal lobule showed greater activation in L2 reading compared to L1 reading. Interestingly, this finding was repeated in both types of bilinguals, suggesting that the extra involvement of the left inferior parietal lobule in L2 reading may be independent of writing system similarity.

The relationship between L.IPL and L2 processing has become evident in recent years. For example, it was reported that gray matter density or volume in L.IPL was significantly higher in bilingual individuals compared to monolingual individuals (Mechelli, Crinion, Noppeney, O'Doherty, Ashburner, Frackowiak & Price, 2004, Abutalebi, Canini, Della Rosa,

Table 2. ALE results of the overlap and differences between L1 and L2 processing in all bilinguals, each type of bilinguals and Chinese-English bilinguals.

Volume	Region	L/R	BA	x	y	Z	Z score
All bilinguals: L1 > L2							
488	Fusiform Gyrus	R	18	32	−96	−12	2.583
280	Middle Frontal Gyrus	L	9	−44	16	38	2.506
L2 > L1							
1000	Inferior Parietal Lobule	L	40	−46	−38	48	3.291
240	Precuneus	R	7	24	−65	44	2.135
160	Insula	L	13	−42	6	−4	2.132
Bilinguals learning two languages with different writing systems (MP bilinguals) L1 > L2							
720	Superior Temporal Gyrus	L	22	−49	−38	4	2.167
376	Fusiform Gyrus	R	18	27	−96	−12	2.130
344	Middle Frontal Gyrus	L	9	−44	18	36	2.518
280	Inferior Frontal Gyrus	L	45	−46	24	14	2.079
L2 > L1							
440	Inferior Parietal Lobule	L	40	−38	−40	44	1.946
320	Fusiform Gyrus	R	37	48	−60	−14	1.913
Bilinguals learning two languages with similar writing systems (PP bilinguals)							
L1 > L2							
	-						
L2 > L1							
456	Inferior Frontal Gyrus	L	46	−44	22	16	2.016
232	Inferior Parietal Lobule	L	40	−46	−39	50	2.142
152	Insula	L	13	−42	6	−6	1.761
Chinese-English bilinguals							
L1 > L2							
696	Superior Temporal Gyrus	L	22	−48	−38	2	2.104
352	Fusiform Gyrus	R	18	28	−96	−12	2.155
344	Middle Frontal Gyrus	L	9	−44	18	36	2.628
264	Inferior Frontal Gyrus	L	45	−46	24	14	2.101
L2 > L1							
392	Inferior Parietal Lobule	L	40	−40	−38	48	1.885
312	Fusiform Gyrus	R	37	48	−60	−14	1.946

Note. Uncorrected $p < 0.05$ with a minimum cluster volume of 100 mm^3.

Green & Weekes, 2015). Gray matter density in this region was positively correlated with multilingual competence (Della Rosa, Videsott, Borsa, Canini, Weekes, Franceschini & Abutalebi, 2013) and L2 proficiency (Mechelli et al., 2004), but negatively correlated with the age of L2 acquisition (Mechelli et al., 2004). Consistent with these results, with magnetoencephalography (MEG), Lerner, Honey, Silbert, and Hasson (2011) reported neural signal change in L.IPL during learning of new names, which was supported by Mestres-Missé, Münte, and Rodriguez-Fornells (2009). Recently, with an immersion second language learning environment, it was further found that activation in L.IPL at time 2 (after L2 learning) positively correlated with reading speed of L2 and could predict gain in reading speed (Barbeau, Chai, Chen, Soles, Berken, Baum, Watkins & Klein, 2017).

Increased activation of L.IPL during reading in L2 could be associated with extra demand in phonological processing. Learning to read, either in the first or second language, involves the integration of orthography, phonology, and semantic information (Achal, Hoeft & Bray, 2015, Huber, Donnelly, Rokem & Yeatman, 2018, Karipidis, Pleisch, Brandeis, Roth, Röthlisberger, Schneebeli, Walitza & Brem, 2018). For reading in the native language, spoken language systems have been developed before reading instruction (Perfetti & Sandak, 2000, Hulme, Hatcher, Nation, Brown, Adams & Stuart, 2002). Extensive oral experience could facilitate phonological processing during reading in L1.

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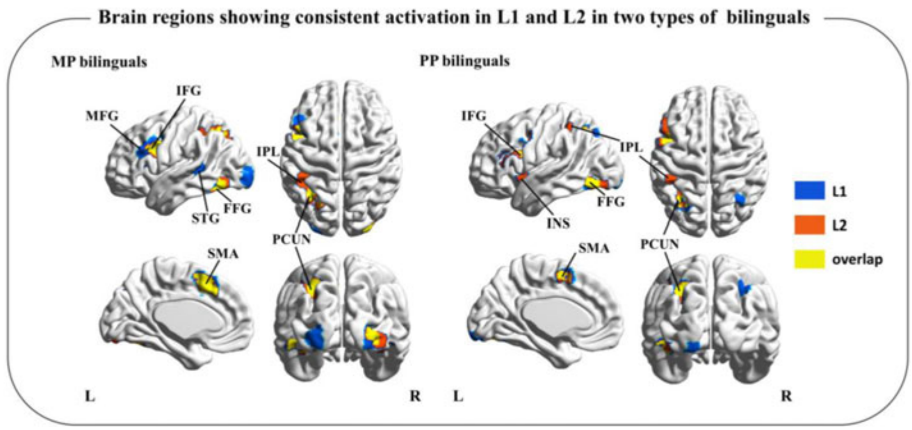

Fig. 2. Brain regions showing consistent activation during L1 and L2 processing in MP bilinguals and PP bilinguals (voxel height $p < 0.001$, cluster $p < 0.05$, FWE-corrected). MP bilinguals = bilinguals speaking two languages with a morphogram writing system and a phonogram writing system; PP bilinguals = bilinguals speaking two languages with phonogram writing systems. The blue region represents the L1 meta-map, the orange region represents the L2 meta-map, the yellow region represents the regions that overlapped in these two maps. MFG = middle frontal gyrus, IFG = inferior frontal gyrus, STG = superior temporal gyrus, IPL = inferior parietal lobule, SMA = supplementary motor area, FFG = fusiform gyrus, INS = insula, PCUN = precuneus.

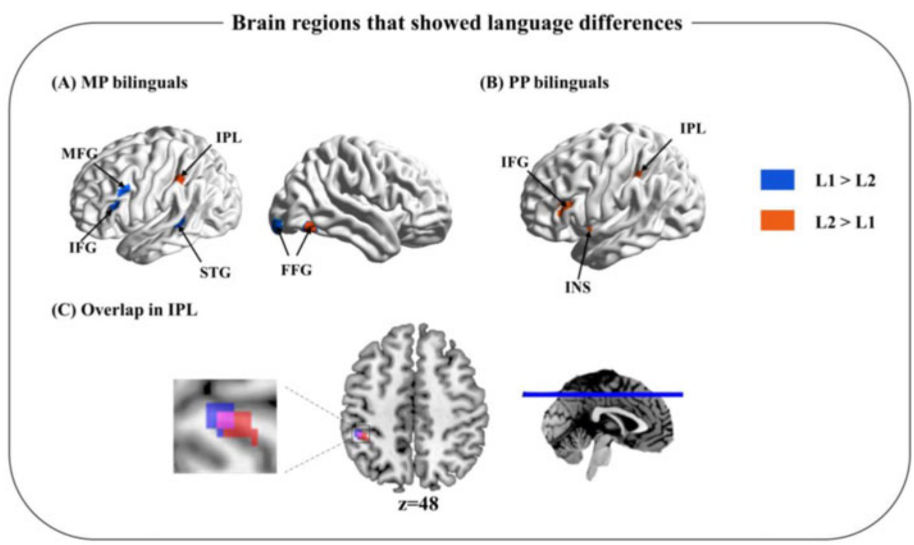

Fig. 3. Brain regions that showed language differences in MP bilinguals (A) and PP bilinguals (B) (uncorrected $p < 0.05$ with a minimum cluster volume of 100 mm3). MP bilinguals = bilinguals speaking two languages with a morphogram writing system and a phonogram writing system; PP bilinguals = bilinguals speaking two languages with phonogram writing systems. Blue regions showed more consistent activation in response to L1 reading than L2 reading. Orange regions showed more consistent activation in response to L2 reading than L1 reading. IPL = inferior parietal lobule, STG = superior temporal gyrus, MFG = middle frontal gyrus, FFG = fusiform gyrus, IFG = inferior frontal gyrus, INS = insula. (C) Topographic relationship of the left inferior parietal lobule observed by comparing the processing of the two languages (L2 > L1) in MP bilinguals (red region) and PP bilinguals (blue region).

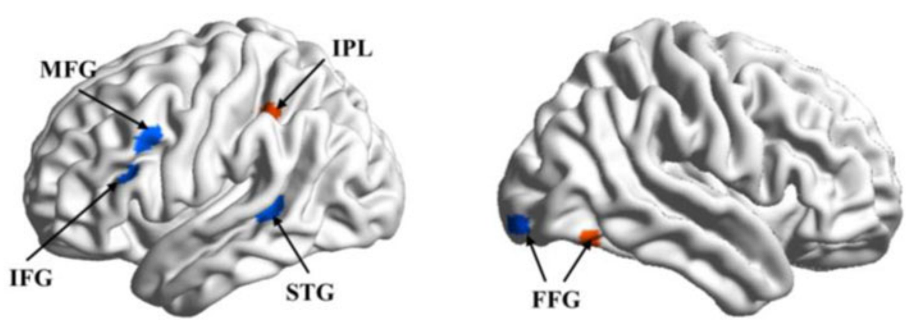

Fig. 4. Brain regions that showed specific language differences in Chinese–English bilinguals. Brain regions obtained from the comparison of the L1 meta-map and the L2 meta-map (uncorrected $p < 0.05$, minimum cluster volume of 100 mm3). Blue regions showed more consistent activation in response to L1 reading than L2 reading. Orange regions showed more consistent activation in response to L2 reading than L1 reading. IPL = inferior parietal lobule, STG = superior temporal gyrus, MFG = middle frontal gyrus, FFG = fusiform gyrus, IFG = inferior frontal gyrus.

However, learning to read in L2 often begins without enough pre-exposure to oral language (Koda, 2005), which could make the phonological processing in L2 more energy consuming than that in L1. As a result, more phonological-related regions might be engaged during reading in L2.

4.2 Writing system similarity influences brain organization for processing two languages

Unlike the left inferior parietal lobule, neural response in other brain regions – including the left middle frontal gyrus, the right posterior fusiform gyrus, the left insula, and the right precuneus – is influenced by the similarity of writing systems between languages. Meta-analyses across all bilinguals showed greater activation in the left middle frontal gyrus and the right posterior fusiform gyrus during reading in L1 compared to that in L2. However, this pattern was only repeated in MP bilinguals. For PP bilinguals, no region showed preferences for L1. The left middle frontal gyrus was once considered as a reading-related region specific to Chinese (Tan, Liu, Perfetti, Spinks, Fox & Gao, 2001, Tan et al., 2003, Tan, Laird, Li & Fox, 2005). However, this does not necessarily mean that the left middle frontal gyrus was

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only responsible for morphogram languages. Instead, recently extensive studies have showed that this region was also engaged in alphabetic reading (Cattinelli, Borghese, Gallucci & Paulesu, 2013, Taylor, Rastle & Davis, 2013, Martin, Schurz, Kronbichler & Richlan, 2015, Murphy, Jogia & Talcott, 2019), perhaps by supporting phonological or semantic retrieving, or visuospatial processing (Perfetti & Liu, 2005, Tan et al., 2005, Perfetti, Liu, Fiez, Nelson, Bolger & Tan, 2007, Siok et al., 2008), which are all fundamental processes for reading. Moreover, activation of this region has been consistently observed in reading continuous text and considered as a part of a putative "extended language network" (Ferstl & von Cramon, 2002, Ferstl, Neumann, Bogler, von Cramon & Cramon, 2008, Mason & Just, 2009, Buchweitz, Mason, Meschyan, Keller & Just, 2014). Concerning the right posterior fusiform gyrus, it was suggested to be implicated in low-frequency visuospatial information processing (Perfetti, Cao & Booth, 2013). Higher activation in these regions in L1 compared to L2 might indicate the extent of utilization of the reading system in L1 during reading in L2. The current results suggest that PP bilinguals would be more likely to make the best use of the reading system of L1 during reading in L2 relative to MP bilinguals.

In contrast, the left insula showed greater activation in L2 than L1. However, this contrasting pattern was only observed in PP bilinguals. The left insula plays a key role in articulation, speech production, or motor processing (Chang, Yarkoni, Khaw & Sanfey, 2012, Carota, Kriegeskorte, Nili & Pulvermüller, 2017, Söderström, Horne, Mannfolk, van Westen & Roll, 2017). More reliance on this region during reading in L2 in PP bilinguals might be ascribed to the high similarity of writing systems. PP bilinguals learned two similar languages. As a result, phonological information of both languages might be activated simultaneously during reading (Kroll, Bobb & Hoshino, 2014). To focus on non-dominant L2, readers might rely on additional neural resources to facilitate phonological processing in L2. For MP bilinguals, instead of relying more on phonological-related regions, reading in L2 induced more activation in visual related regions, i.e., the right anterior fusiform gyrus (BA37), which was next to the right posterior fusiform gyrus (BA18) that prefers L1. Segregated neural correlates of L1 and L2 associated with visual processing could be due to the remarkable difference in visual appearance of two languages learned by MP bilinguals. In the current study, the morphogram languages were Chinese and Japanese Kanji. Graphic units of them consist of intricate strokes with square configurations, whereas for phonogram languages (English in the present study), words are formed with letters organized in linear structures. Difference in physical properties in word form might contribute to the neural separations during visual word processing across languages. Increased activation in L2 might indicate the adaptation of the brain to a new language. The current results suggest that adaptation pattern to a new language was influenced by the writing system similarity.

Previous meta-analyses of the brain organization of bilinguals learning two languages are mainly based on a broader language level and focused on the effect of two factors: language proficiency (Sebastian et al., 2011) and the age of second language acquisition (AoA of L2, Liu & Cao, 2016). However, few studies have ever focused on bilingual reading. As the core process of reading, integrating orthographic information with phonology or semantic information might be influenced by the writing systems, it is of great interest to depict the neural correlates of L1 and L2 for different bilinguals. The current study specifically focused on the effect of the similarity of writing system across languages on brain organization for reading in two languages, which improves our understanding of how one brain adapts to various languages.

4.3 Implications for theories related to bilingual reading

One of the hottest issues over bilingual reading concerns how one brain reads in two languages (Perfetti et al., 2007, Nelson et al., 2009, Xu et al., 2017). The system assimilation hypothesis proposed that reading in a second language utilizes the neural system of the first language (Perfetti et al., 2007, Nelson et al., 2009). Consistent with this claim, it was suggested that cognitive processes engaged in reading in first languages, such as phonological, orthographic, and semantic processes, lay the foundation for reading in L2 (Sparks, 1995). Problems with one or more of these processes will negatively influence the acquisition of second language (Sparks, Ganschow & Pohlman, 1989, Sparks & Ganschow, 1993, Sparks, 1995). However, a pure assimilation pattern might not be practicable, which is complemented by the system accommodation hypothesis that the brain might allocate additional neural resources to adapt to a new language (Hasegawa et al., 2002). However, until now, which and how regions are specifically involved in L2 remains an open question. Here we observed with meta-analyses that three regions – including the L.IPL, the left insula, and the right precuneus – showed higher activation during reading in L2 compared to that in L1. As mentioned before, the L.IPL might be associated with increased phonological demand, and the left insula might be connected to articulation. Stronger brain signals in these regions indicate that accommodation process could be partly driven by phonological processing in L2 reading.

Notably, previous studies showed that orthographic depth might modulate the assimilation and accommodation pattern (Liu & Cao, 2016). For example, for Chinese–English bilinguals, the orthographic depth of Chinese (L1) is deeper than that of English (L2). It was suggested that the neural system for Chinese processing can be applied to reading in English; whereas, for English–Chinese bilinguals, the brain might recruit more regions to adapt to the sophisticated visual properties and different phonological accessing pathway of Chinese. Therefore, L2 reading in Chinese–English bilinguals follows an assimilation pattern, whereas L2 reading in English-Chinese bilinguals complies with an accommodation pattern (Nelson et al., 2009). Here we found that reading in L2 elicited greater activation in the left inferior parietal lobule compared to reading in L1, which offered evidence for the accommodation pattern. This result contributes to solving the discrepancy findings in Chinese–English bilinguals and suggests that additional neural resources in L.IPL might be a common signature for reading in L2.

4.4 Limitations of meta-analytic studies

There are two main limitations associated with meta-analytic studies. First, we used a coordinate-based meta-analysis rather than an image-based meta-analysis. An image-based meta-analysis is based on full statistical images, which is a better representation of the original data. However, since most of the previous studies do not share the statistical images on the whole brain level, image-based meta-analyses might not be practicable (Müller, Cieslik, Laird, Fox, Radua, Mataix-Cols and Wager, 2017). Therefore, coordinate-based meta-analysis was performed, as coordinates were reported in almost all previous neuroimaging studies (Müller et al., 2017). Second, coordinate-based

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meta-analyses does not take the thresholds for significance into consideration, which makes it difficult to weigh the importance of coordinates from different studies. Further studies are required to address these limitations.

5. Conclusions

Comparisons between L1 and L2 revealed that reading in L2 may rely more on the left inferior parietal lobule compared to L1, which pattern seems to be independent of writing system similarity across languages. More engagement of this region might be associated with increased phonological processing demand for L2 processing. In addition, MP bilinguals showed different patterns from PP bilinguals as to the comparison between neural correlates of L1 and L2 reading, suggesting that the writing system similarity influences the brain organization for different languages.

Declarations of interest

The authors have no conflicts of interest to declare.

Supplementary Material. For supplementary material accompanying this paper, visit https://doi.org/10.1017/S136672892000070X

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