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How does the brain read different scripts? Evidence from English, Korean, and Chinese

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Abstract

Writing systems differ in various aspects. English and Korean share basic principles of the alphabetic writing system. As an alphabetic script, Korean Hangul has relatively more regular mapping between graphemes and phonemes; however, its letters are written in syllable units, which encourages phonological retrieval at the syllable level. Therefore, we are interested in whether Korean is similar to English in terms of their brain activation because both are alphabetic, as well as whether Korean is similar to Chinese due to their reliance on syllable-level phonological retrieval. This study compared brain activation patterns during a visual rhyming judgment task in English, Korean, and Chinese. The results revealed that among the three languages, Korean and Chinese showed greater similarities in brain activation than either of them showed with English. Specifically, English recruited the left inferior frontal gyrus, left fusiform gyrus, and left superior temporal gyrus to a greater degree than did Korean or Chinese. In contrast, Korean and Chinese elicited greater activation than English in the bilateral middle frontal gyri, left inferior parietal lobule, and precuneus. These findings suggest that the brain network for Korean is not simply depicted as the one typically observed with alphabetic scripts (e.g., English) but rather highly similar to that of Chinese, a morpho-syllabic script, possibly because the Korean writing system leads to syllable-level phonological representation and processing.

Keywords Scriptal effect · Reading · Visual word processing · fMRI · English · Korean · Chinese

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Introduction

Universality of the reading network across languages

The present study addresses a longstanding question of whether and to what extent different brain networks are recruited in processing different language scripts. Much evidence has supported the claim that reading involves a highly universal brain network (e.g., Nakamura et al., 2012; Perfetti, 2003; Perfetti & Tan, 2013). This universality of brain networks activated across languages can be explained from an evolutionary perspective (Dehaene & Cohen, 2007; Hernandez et al., 2019) or the universal constraints of spoken words on written words (Frost et al., 2009; Rueckl et al., 2015). For example, *the neuronal recycling hypothesis* postulates that reading (and writing) is supported by brain regions and networks that are initially involved in relevant visual functions (e.g., face recognition) and language functions. Indeed, researchers have located the "visual word form area" in the left-mid occipitotemporal region that borders the left fusiform face area (FFA; Bouhali et al., 2014). Based on a meta-analysis of studies examining alphabetic and logographic languages, Bolger et al. (2005) has presented evidence for a universal reading network, including the left superior posterior temporal gyrus, left inferior frontal gyrus, left occipitotemporal region, and mid-fusiform gyrus. The left occipitotemporal regions are involved in orthographic recognition (Dehaene & Cohen, 2007, 2011). The left inferior frontal gyrus is involved in phonological retrieval and selection (Costafreda et al., 2006; Katzev et al., 2013), and the left superior temporal gyrus is involved in phonological representation (Binder et al., 2000; Sekiguchi et al., 2004) and phonological assembly (Pugh et al., 2000; Twomey et al., 2015).

Numerous neuroimaging studies also provide evidence for language's universality with some variations due to the brain's language specificity (e.g., Bolger et al., 2005; Perfetti et al., 2013; Rueckl et al., 2015; Tan et al., 2005). In the meta-analysis of alphabetic and logographic languages, Bolger et al. (2005) also found some regions that are sensitive to writing system variations. For example, although both anterior and lateral regions of the superior temporal gyrus were commonly activated across all languages, its posterior regions were sensitive to English and Japanese Kana but not to Chinese or Japanese Kanji (Bolger et al., 2005). This difference probably occurred because English and Japanese Kana share the phonological assembly procedure, whereas Chinese and Japanese Kanji do not. Thus, the nature of mapping between script and sound plays an important role in determining the brain regions involved in reading (Tan et al., 2005).

Language differences in the reading network

According to the dual-route model of reading (Coltheart et al., 2001), there are two possible mechanisms for the conversion of script to speech: (1) the lexical route in which a word directly maps to sound and (2) the sub-lexical route in which graphemes map to phonemes. Cross-linguistic neuroimaging studies support the two routes' distinctiveness. Paulesu et al. (2000) demonstrated a language effect in which differential reading networks were involved in different languages (Italian or English) depending on whether the language's writing system is transparent (regular mappings between graphemes and phonemes) or opaque (irregular mappings between graphemes and phonemes). In transparent systems, the sub-lexical route tends to be employed more often than the lexical route, whereas in opaque systems, the lexical route is employed more often (Fiez et al., 1999), as there is more consistent mapping in the former group than in the latter. For example, in Italian (a transparent orthographic system), dorsal brain regions are recruited, namely the left superior posterior temporal regions, while in English (an opaque system) ventral brain regions are engaged, namely the left inferior temporal gyrus and anterior inferior frontal gyrus (Paulesu et al., 2000). For languages that utilize the Latin alphabet, orthographic depth impacts reading strategies and is reflected in the brain. However, some researchers opine that this argument is rather simplistic, and the concept of orthographic depth has not been defined precisely (for discussion, see Schmalz et al., 2015). Supporting evidence for the dual-route model also comes from comparisons between inconsistent and consistent words (Fiez et al., 1999), exceptional words and pseudowords (Fiebach et al., 2002), Chinese character reading and pinyin reading (Pinyin is an alphabet system labeling the sound of a character; Chen et al., 2002), and Japanese Kanji and Kana reading (Thuy et al., 2004), with the former involving the lexical route and the latter involving the sub-lexical route.

Chinese, a morpho-syllabic writing system, has frequently been compared with alphabetic writing systems, such as English (e.g., Bolger et al., 2005; Tan et al., 2005) and French (Nakamura et al., 2012). Undoubtedly, the comparison between Chinese and alphabetic writing systems provides compelling evidence showing both universal and specific patterns across languages (Nakamura et al., 2012; Perfetti et al., 2013; Rueckl et al., 2015). For example, there is greater activation in the right middle occipital gyrus and fusiform gyrus in Chinese than in English (Bolger et al., 2005; Cao et al., 2013; Tan et al., 2005) due to Chinese characters' complex visual configuration. Chinese also produces greater activation in the left middle frontal gyrus than English due to the addressed phonological retrieval (Booth et al., 2006; Siok et al., 2008; Tan et al., 2005), while English produces greater activation in the left posterior superior temporal gyrus than Chinese due to the phonological assembly (Bolger et al., 2005). These language differences in the brain are consistent with the features of Chinese and English. In Chinese, each character is mapped to the whole syllable, and each character visually consists of strokes packed into a two-dimensional square, while English features a left-to-right linear layout of letters that represents phonemes. Taken together, including a third language that shares some characteristics with alphabetic languages (English) and other characteristics with morpho-syllabic languages (Chinese) in the comparison would more precisely explain the relationship between brain activation and language features.

Korean and its reading network

As an alphabetic system, the Korean script Hangul comprises 14 consonant letters and 10 basic vowel letters. The letters are uniquely organized into syllabic blocks, from left to right and/or from top to bottom (e.g., the three letters ㅎ, ㅏ, and ㄴ are packaged into the syllable 한 /han/). Because each syllabic block in Korean is visually distinct (e.g., two syllables in the word 한글, /han.gul/), Korean is often considered an alphabetic syllabary or syllabic alphabet (e.g., Pae, 2011; Taylor, 1980). Hence, Korean Hangul has a unique status among alphabetic orthographies in terms of its alphabetic syllabary mapping and visual-orthographic configuration (nonlinear visual arrangement). Although Korean is alphabetic, it is similar to Chinese in that each character represents a syllable, which encourages syllable-level rather than phoneme-level phonological processing. Note, however, that sub-syllabic units are also activated in Korean word recognition, including individual letters (Lee, 1999) or the body unit (Lee & Taft, 2011; Yoon et al., 2002). In terms of orthographic depth, Korean is more transparent than English, as the sound-letter mapping is quite consistent (Pae, 2018). Additionally, there is one-to-one sound-letter mapping, although some phonological variations occur. Table 1 shows major characteristics of English, Korean, and Chinese. By comparing these languages, we can ascertain how written language characteristics are represented in the brain. Along the two dimensions of differences—the visual form and the mapping rule between orthography and phonology—English and Korean may converge somewhat in their alphabetic mapping between orthography and phonology. In contrast, Korean and Chinese may activate similar regions due to the similar structure of written forms in their nonlinear visual-spatial layout. However, Korean may be more similar to Chinese than to English in phonological mapping because of Korean's syllable-level phonological retrieval. Therefore, this study is unique in testing whether the alphabetic nature or Korean letters being written in a nonlinear layout via syllable plays a more important role in phonological processing during reading.

To date, there have been a few fMRI studies examining brain activation during Korean reading (e.g., Kim et al., 2004; Lee, 2004; Yoon et al., 2005a, 2005b). One study showed that Hangul words, as compared to pictures of concrete nouns such as "cat" or "desk", elicited greater activation in the left middle frontal gyrus (Yoon et al., 2005a, 2005b). Interestingly, Chinese has consistently been associated with greater activation in the left middle frontal gyrus and bilateral temporo-occipital regions compared to English and Japanese Kana (Bolger et al., 2005; Tan et al., 2005). Therefore, some overlap can be expected in these regions between Korean and Chinese, despite the stark differences in their writing systems. Yoon et al., (2005a, 2005b) also demonstrated greater activation in the left superior temporal

Table 1 Characteristics of the three Languages

	English	Korean	Chinese
Writing system	Alphabetic	Alphabetic syllabary	Morpho-syllabic
Script arrangement	Linear layout	Nonlinear layout	Nonlinear layout
Script-to-sound mapping (at letter level)	Quasi-regular via grapheme units	Moderately regular via grapheme units	No grapheme-phoneme correspondence, but phonetic radicals
Example	north/nɔːθ/	북/puk/	北/běi/

gyrus, right superior frontal gyrus, right middle temporal gyrus, and right precentral gyrus in participants reading Hangul compared to those reading Hanja (i.e., Chinese characters used in Korean). Therefore, it is also reasonable to expect differences between Korean and Chinese in terms of brain networks activated.

Based on previous findings, this study was designed to compare brain activation patterns across three languages (English, Korean, and Chinese) during a visual rhyming judgment task. We used a visual rhyming judgment task because this task explicitly requires conversion from script to sound, and the mechanism of this conversion varies depending on orthographic depth. We expected to uncover both similarities and differences in brain mechanisms underlying visual form processing, conversion from orthography to phonology, and rhyming judgment in the three different languages. As Korean and Chinese share a nonlinear layout of scripts, we expected similarities between Korean and Chinese in their activation of visuo-orthographic brain regions. Additionally, Korean and English share alphabetic principles, and we expected similarity between Korean and English in phoneme-level phonological processing regions. Finally, Korean and Chinese share syllable-level phonological retrieval, and we expected similarity between Korean and Chinese in addressed phonological regions.

Methods

Participants

Twenty-seven native Korean speakers (mean age = 21.6 years, *SD* = 2.2) and 20 native Chinese speakers (mean age = 21.0 years, *SD* = 3.5) were recruited in Beijing. Additionally, 24 native English speakers' data were retrieved from an open database—OpenNeuro (Lytle et al., 2020) (mean age = 21.5 years, *SD* = 2.2; participants were recruited in Chicago, Illinois.). All participants were right-handed, were 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 boards at Beijing Normal University approved the informed consent procedures.

Task

During functional magnetic resonance imaging (fMRI), participants performed a rhyming judgment task on sequentially presented visual word pairs in their native language (English, Korean, or Chinese), mixed with perceptual control and baseline trials. For the task, participants were presented with word pairs on the screen one at a time and were instructed to judge as quickly and accurately as possible whether the two words rhymed, using their right index finger for "yes" and their right middle finger for "no." For each trial, each stimulus appeared for 800 ms, with a 200-ms blank interval between stimuli. A red fixation cross appeared on the screen immediately after the offset of the second stimulus in the pair, indicating the need to provide a response. The inter-trial interval was jittered (2,200, 2,600, or 3,000 ms), such that each trial lasted for 4,000, 4,400, or 4,800 ms. For resting baseline trials ($N=48$), participants pressed the “yes” button when a black fixation cross appeared in the center of the screen. Additionally, perceptual control trials ($N=24$) were included as part of a larger project and not analyzed in the current study, in which participants made a same/different judgment for two symbols they just encountered. Different visual symbols were used in the three languages to control for the complexity of each orthography. The timing for the perceptual control and resting baseline trials was the same as that for the lexical trials. The order of presentation for the lexical, perceptual, and resting baseline trials and the variation of the response interval were optimized for event-related designs using OptSeq (http://surfer.nmr.mgh.harvard.edu/optseq).

As shown in Table 2, there were four total conditions: two rhyming and two non-rhyming conditions. The rhyming conditions featured stimuli with similar orthographic and phonological endings (O+P+) and those with different orthographic but similar phonological endings (O−P+). The non-rhyming conditions featured stimuli with the same orthographic but different phonological endings (O+P−) and those with different orthographic and phonological endings (O−P−). We included these four conditions for participants to execute the mapping from script to sound, as a judgment cannot be made based solely on orthography. To avoid homophonic items, all the English stimuli were monosyllabic, but the Chinese and Korean stimuli were disyllabic. Participants were instructed to judge the ending sounds of the two words in Chinese or Korean. We did not consider suprasegmental features (such as tones) when determining the rhyming effects. However, half of the trials had the same tone, while the other half had different tones. Each condition included 24 trials except that there were no items available for the O+P− condition (e.g., pint-mint in English) in Korean due to its transparent mapping system. We matched stimuli across conditions for written word frequency and the sum of their written bigram frequency according to databases based on each language (for English, English Lexicon Project, http://elexicon.wustl.edu; for Chinese, Beijing Language and Culture University, 1990; for Korean, Korean Word Database, Sejong corpus, 2003). Additionally, we matched word frequency in all three languages [$F(2, 516)=2.158$, $p=0.117$].

Table 2 Examples of stimuli in each condition for the three languages

Condition	Language		
	English	Korean	Chinese
O+P+	late-hate	화분/hwabun/—교문/kyomun/	弥补/mi2bu3/—纯朴/chun2pu3/
O–P+	jazz-has	정답/tsʌŋdap/—술값/sulkap/	环保/huan2bao3/—大炮/da4pao4/
O+P−	pint-mint	N/A	翻译/fan1yi4/—选择/xuan3ze2/
O–P−	press-list	신발/sinbal/—영혼/yʌŋhon/	损坏/sun3huai4/—学科 /xue2ke1/

O: orthography; P: phonology; +: similar; −: different

The numbers refer to the four tones in Chinese

MRI data acquisition

For the English data from OpenNeuro (Lytle et al., 2020), native English speakers were recruited in Chicago, whose brain images were acquired using a 3.0 T Siemens scanner (Siemens Healthcare) at Northwestern University. Native Korean and Chinese speakers were recruited in Beijing, and all images were acquired at Beijing Normal University using an identical scanner and the same protocol as for native English speakers. Previous studies have demonstrated that variability across sites is rather small, reproducibility is similar between and within sites (Gountouna et al., 2010; Sutton et al., 2008), and the effect of the scanner is much less significant than the effect of the group, with no interaction between these two variables (Stonnington et al., 2008).

During scanning, participants lay in the scanner with their head position secured with foam padding. Each participant held an optical response box in their dominant right hand and a compression alarm ball in their left hand. The head coil was positioned over each participant's head such that they could effectively use the mirror to view the projection screen at the rear of the scanner. Gradient echo localizer images were acquired to determine the placement of the functional slices. For the functional images, a susceptibility weighted single-shot echo planar imaging (EPI) method with blood oxygenation level-dependency (BOLD) was used with the following scan parameters: TR = 2,000 ms, TE = 20 ms, flip angle = 80°, matrix size = 120 × 128, field of view = 220 × 206.3 mm, slice thickness = 3 mm (0.48 mm gap), number of slices = 32. These parameters resulted in a 1.7 × 1.7 × 3 mm voxel size. Using an interleaved bottom-to-top sequence, 145 whole-brain volumes were acquired for each run. A high-resolution, T1 weighted 3D image was also acquired using MP RAGE with the following parameters: TR = 2,300 ms, TE = 3.36 ms, flip angle = 9°, matrix size = 256 × 256, field of view = 256 mm, slice thickness = 1 mm, number of slices = 160, resulting voxel size = 1 × 1 × 1 mm. The acquisition of the anatomical scan took approximately 9 min, and the fMRI scan for each run was 6 min and 44 s for the Chinese and English task and 4 min and 58 s for the Korean task. There were two runs for each language task.

Image analysis

We performed data analysis using DPARSF (Yan and Zang, 2010; http://rmfri.org/DPARSF) and SPM12 (www.fil.ion.ucl.ac.uk/spm). We followed six steps for data preprocessing: (1) slice timing correction for interleaved acquisition using sinc interpolation, (2) 4th degree b-splice interpolation for realignment to the first volume, (3) trilinear coregistration with the anatomical image, (4) segmentation of the anatomical image, (5) normalization of all brains to the standard T1 Montreal Neurological Institute (MNI) adult template with a voxel size = 2 × 2 × 2 mm (12 linear affine parameters for brain size and position, 8 non-linear iterations and non-linear basis functions), and (6) 4 × 4 × 8 mm full width half maximum Gaussian kernel smoothing. Up to one volume, where movement exceeded 3 mm in any of the x, y, or z dimensions, was replaced with the mean of the images immediately before and after the outlying volume. We excluded participants with > 1 volume or > 3 mm of movement from further analysis. Statistical analyses at the first level proceeded using an event-related design with lexical conditions, perceptual control trials, and baseline trials. We applied a high-pass filter with a cutoff period of 128 s. Trials were modeled using a canonical hemodynamic response function (HRF).

In SPM12, we obtained group results using random-effects analyses in a general linear model combining participant-specific summary statistics across the group. We calculated the contrast of rhyming trials (including O + P + and O − P +) > fixation baseline trials using separate one-sample *t*-tests for each language group. As we were also interested in visual effects, we compared rhyming trials with the resting baseline trials rather than the perceptual control trials, and we attempted to identify brain activation related to visual form processing through subtraction (rhyming − resting baseline). We included only the two rhyming conditions (O + P +, and O − P +) in the analysis because responses in the non-rhyming conditions might be qualitatively different from those in the rhyming conditions (e.g., whole syllable comparison rather than rhyming judgment) and the number of trials differed among the three languages (i.e., no O + P − condition for Korean). We conducted a series of overlap analyses to capture the parts of the brain commonly activated in various combinations among the three languages. First, we calculated the overlapped brain regions between each pair of languages, as well as across the three languages. We also identified brain regions that overlapped in a particular pair of languages but not in other pairs (e.g., overlap between Korean and English but not between English and Chinese or between Korean and Chinese).

For the group comparison, we conducted a series of independent sample *t*-tests: English vs. Korean, English vs. Chinese, and Korean vs. Chinese. Additionally, we performed several conjunction analyses to identify any brain region uniquely involved in one language versus the other two languages. Namely, we examined the conjunctions of English > Korean (i.e., regions that were more activated for English than for Korean) and English > Chinese (i.e., regions that were more activated for English than for Chinese) for English; Korean > English and Korean > Chinese for Korean; and Chinese > English and Chinese > Korean for Chinese. Subsequently, to identify any regions shared by each pair of languages, we conducted the following conjunction analyses: English > Chinese and Korean > Chinese; English > Chinese and Chinese > Korean; and Korean > English and Chinese > English.

Throughout the imaging analyses, we regressed both accuracy and reaction times (RTs) as covariates. We applied thresholds of uncorrected $p < 0.001$ at the voxel level and false discovery rate (FDR) corrected $p < 0.05$ at the cluster level for all *t*-tests and conjunction analyses. BrainNet viewer visualized all brain images (Xia et al., 2013).

Results

Behavioral performance

We conducted a series of ANOVA of language on accuracy and RTs, respectively (Table 3). For accuracy, the main effect of language was significant [$F(2, 68) = 11.268$, $p < 0.001$]. Planned comparisons revealed that accuracy for English was significantly higher than that for Chinese [$F(1, 42) = 8.474$, $p = 0.006$], and accuracy for Korean was higher than that for Chinese [$F(1, 42) = 22.739$, $p < 0.001$]. We found no difference between English and Korean ($p = 0.140$). For RTs, the main effect of language was also significant [$F(2, 68) = 4.268$, $p = 0.018$]. Similarly, RTs for English and Korean were significantly faster than those for Chinese [$F(1, 42) = 6.857$, $p = 0.012$ for English; $F(1, 45) = 4.445$, $p = 0.041$ for Korean]. Further, we found no difference between English and Korean ($p = 0.303$).

Brain activation patterns

Table 4 and Fig. 1 show evidence for greater brain activations for the rhyming judgment compared to the resting baseline (i.e., rhyming trials > fixation in each language) in each group. The English group showed significant activation in the bilateral fusiform gyri, left inferior temporal gyrus, superior parietal lobule, inferior frontal gyrus, medial frontal gyrus, middle frontal gyrus, superior temporal gyrus, right middle occipital gyrus, lingual gyrus, and cuneus. The Korean group showed activation in the bilateral inferior/middle occipital gyri, left inferior/middle frontal gyri, medial frontal gyrus, fusiform gyrus, inferior parietal lobule, cuneus, putamen, right inferior/middle frontal gyrus, and superior parietal lobule. The Chinese group showed activation in the bilateral inferior occipital gyri, lingual gyri, inferior/middle frontal gyri, left medial frontal gyrus, and precuneus.

The overlap analysis identified the general reading network among the three languages, as shown in Table 5 and Fig. 2. This network includes the posterior occipitotemporal regions (bilateral middle occipital gyri, inferior/middle/superior frontal gyrus, and superior parietal lobule).

We also identified regions that overlapped more in one pair of languages than in other pairs (Table 6 and Fig. 3). Korean and English, in comparison to English and Chinese or Korean and Chinese, showed more overlap in the left inferior/middle/medial frontal gyrus, inferior parietal lobule, precentral gyrus, posterior cingulate, putamen, and right cuneus. Korean and Chinese, compared to English and Chinese or Korean and English, showed more overlap in the bilateral cuneus, left inferior/middle frontal gyrus, middle temporal gyrus, and right precuneus. Chinese and English showed more

Table 3 Means and standard deviations of behavioral performance in each language group

	English	Korean	Chinese
Accuracy (%)	96.4 (4.0)	97.8 (2.7)	92.5 (4.8)
RT (ms)	970 (314)	1050 (237)	1224 (328)

Table 4 Brain activations for the contrast of rhyming minus baseline for each group

Anatomical Region	H	BA	Voxels	x	y	z	Z
English							
Inferior temporal gyrus, fusiform gyrus	L	20, 37	2207	−50	−50	−20	6.23
Superior parietal lobule	L	7	1387	−28	−62	46	5.26
Inferior frontal gyrus	L	46	2466	−46	40	6	5.09
Medial frontal gyrus	L	6	319	−2	14	52	5.06
Middle occipital gyrus	R	19	340	46	−80	2	5.06
Fusiform gyrus	R	37	80	38	−42	−20	4.91
Cuneus, lingual gyrus	R	17,19	1499	16	−72	10	4.60
Middle frontal gyrus	L	6	68	−24	−8	52	4.26
Superior temporal gyrus	L	22	103	−54	−40	8	4.25
Cuneus	R	17	113	22	−94	−2	4.09
Korean							
Middle occipital gyrus, fusiform gyrus, inferior parietal lobule	L	37, 19, 39	4661	−46	−66	−12	7.49
Lingual gyrus, middle occipital gyrus, inferior occipital gyrus	R	17, 18, 19	2626	16	−88	−8	7.25
Inferior frontal gyrus, middle frontal gyrus	L	9	2660	−50	10	30	6.74
Medial frontal gyrus	L	8	399	−6	14	52	5.78
Superior parietal lobule	R	40	346	30	−58	46	5.30
Inferior frontal gyrus	L	47	157	−28	28	−2	5.23
Inferior frontal gyrus	R	47	105	30	28	−2	5.18
Middle frontal gyrus	R	10	60	40	32	22	5.07
Middle frontal gyrus	L	6	48	−26	−2	58	4.81
Cuneus	L	30	59	−12	−66	6	4.68
Putamen	L	-	116	−18	8	0	4.62
Lingual gyrus	R	30	37	20	−60	4	4.28
Chinese							
Inferior occipital gyrus	L	19	2514	−38	−82	−8	6.60
Lingual gyrus	R	17	3570	18	−92	0	6.36
Middle frontal gyrus	L	9	1290	−46	12	32	6.18
Medial frontal gyrus,	L	8	544	−4	20	50	5.95
Precuneus	L	7	494	−30	−58	42	5.51
Middle frontal gyrus	L	6	360	−28	0	68	5.28
Inferior frontal gyrus	L	47	203	−32	26	4	4.95
Middle frontal gyrus	R	6	54	24	−4	50	4.94
Inferior frontal gyrus	R	47	50	38	22	−6	4.62
Posterior cingulate	–	30	81	−2	−68	8	4.49

overlap in the left cuneus, inferior/superior frontal gyrus, precentral gyrus, and right inferior occipital gyrus than did Korean and English or Korean and Chinese.

Table 7 and Fig. 4 present the group comparison results. Compared to Korean, English produced greater activation in the bilateral middle occipital gyri, left medial

Fig. 1 Brain Activation Maps for the Contrast of Rhyming Minus Fixation Baseline in English, Korean, and Chinese

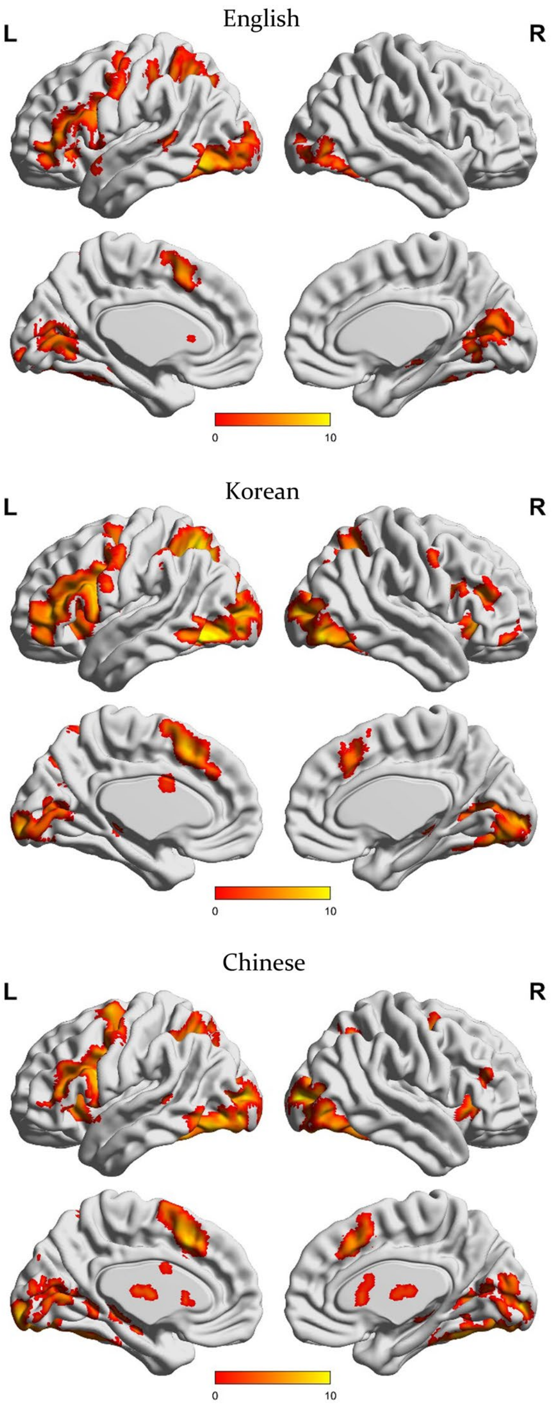


Table 5 Brain activation with overlapped languages

Anatomical Region	H	BA	Voxels	x	y	z	Z
English and Korean and Chinese							
Middle occipital gyrus	L	19	1110	−44	−66	−12	6.39
Inferior frontal gyrus	L	9	728	−48	10	32	5.38
Superior parietal lobule	L	40/7	464	−28	−58	44	5.20
Superior frontal gyrus	L	8	256	−2	26	54	5.15
Middle occipital gyrus	R	19	208	46	−78	−2	4.75
Middle frontal gyrus	L	6	50	−22	−8	54	3.74
English and Korean							
Middle occipital gyrus	L	19	3041	−46	−66	−12	Inf
Inferior frontal gyrus	L	9	2351	−50	12	26	6.57
Medial frontal gyrus	L	8	369	−4	20	48	6.06
Inferior frontal gyrus	L	47	126	−28	28	−2	5.01
Cuneus	R	23	278	12	−70	8	4.99
Middle occipital gyrus	R	19	261	46	−78	−2	4.75
Posterior cingulate	L	30	178	−6	−68	8	4.15
Middle frontal gyrus	L	6	98	−24	−8	52	4.08
English and Chinese							
Middle occipital gyrus	L	19	1205	−46	−66	−12	6.39
Inferior frontal gyrus	L	19	768	−48	19	21	5.38
Superior parietal lobule	L	40/7	486	−28	−58	44	5.20
Superior frontal gyrus	L	8	287	−2	16	54	5.15
Middle occipital gyrus	R	19	283	46	−78	−2	4.75
Inferior frontal gyrus	L	13	171	−38	24	0	4.60
Lingual gyrus	R	17	49	20	−94	−8	4.11
Inferior parietal lobule	L	40	81	−42	−42	44	4.00
Cuneus	L	18	224	−2	−80	2	3.76
Korean and Chinese							
Cuneus	R	18	1799	18	−90	2	7.01
Middle occipital gyrus	L	19	1751	−44	−66	−12	6.39
Middle occipital gyrus	L	19	935	−48	6	34	5.46
Inferior parietal lobule	L	40	752	−30	−56	44	5.37
Medial frontal gyrus	L	8	277	−2	18	52	5.18
Inferior frontal gyrus	L	13	105	−30	22	−2	4.79
Middle frontal gyrus	L	6	77	−26	−4	54	3.80

frontal gyrus, superior parietal lobule, inferior frontal gyrus, middle frontal gyrus, precentral gyrus, superior temporal gyrus, right cuneus, and parahippocampal gyrus. Compared to English, Korean words elicited greater activation in the bilateral middle frontal gyri, left precuneus, superior frontal gyrus, right supramarginal gyrus, inferior parietal lobule, and precentral gyrus.

Compared to Chinese, English produced greater activation in the left fusiform gyrus, superior parietal lobule, inferior frontal gyrus, medial frontal gyrus, superior temporal

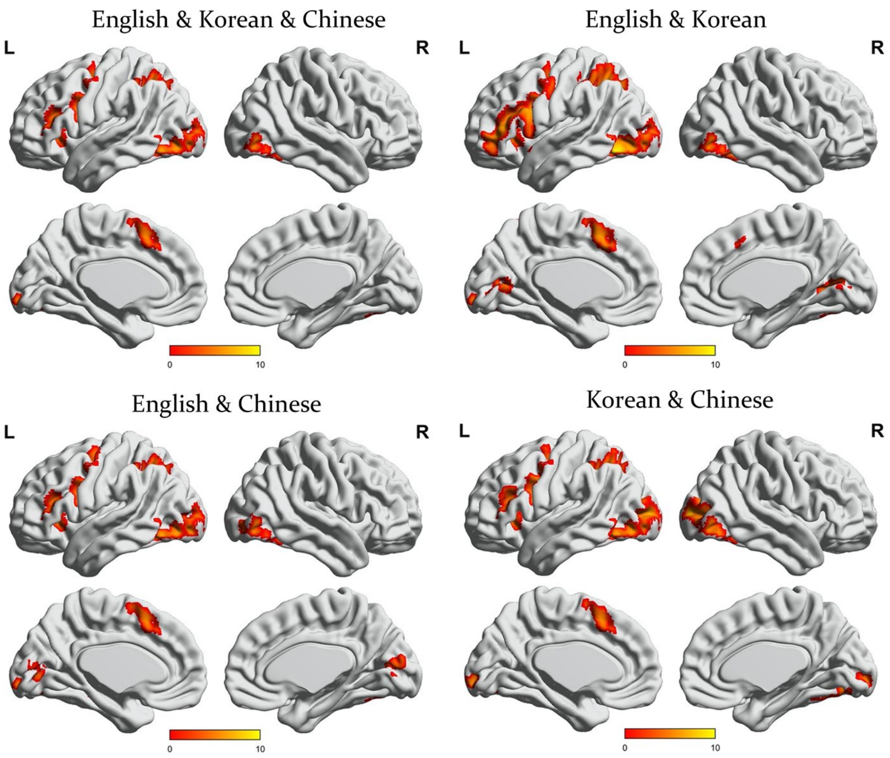
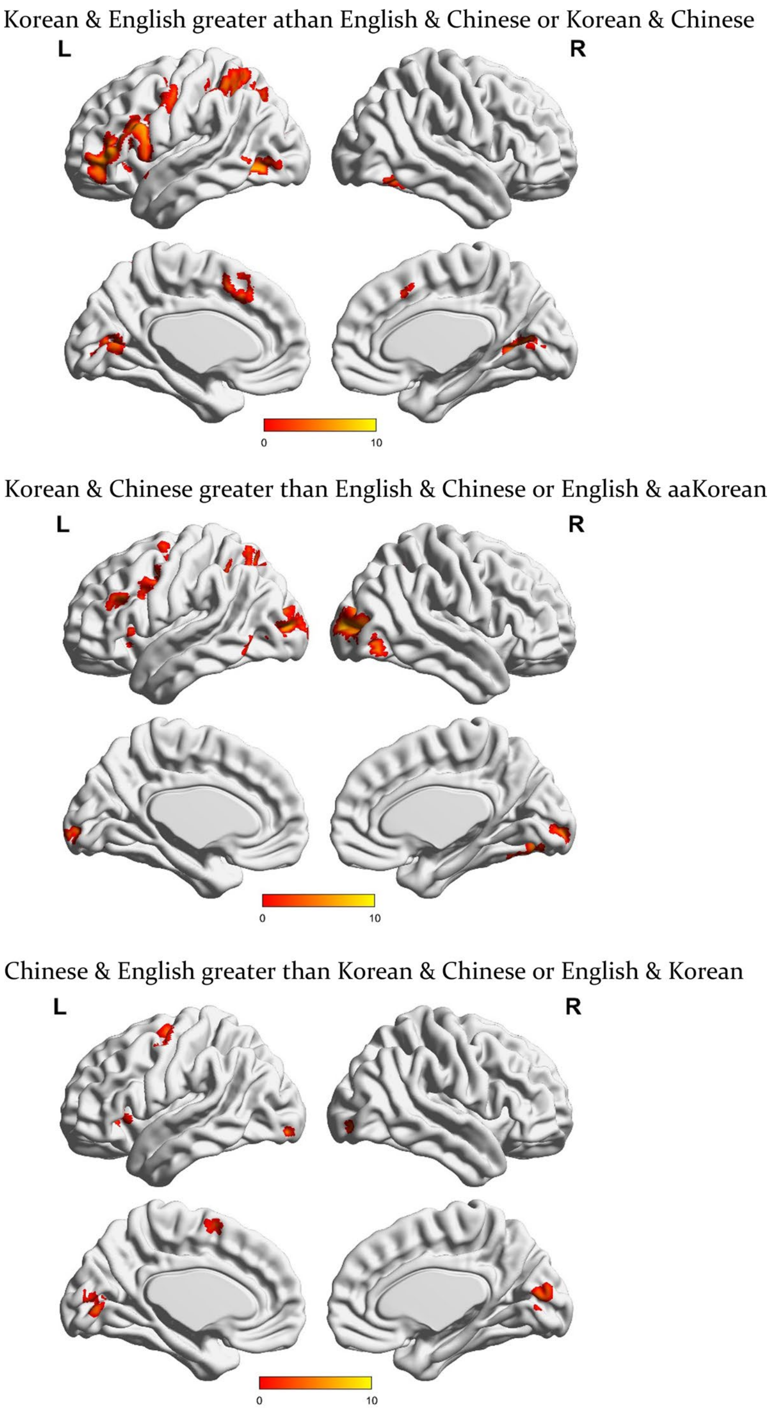


Fig. 2 Overlap of activated brain regions between languages

Table 6 Brain activation with greater overlap in one pair of languages than other two pairs

Anatomical Region	H	BA	Voxels	x	y	z	Z
Korean-English > English-Chinese or Korean-Chinese							
Inferior frontal gyrus	L	9	1535	−52	12	26	6.50
Inferior parietal lobule	L	40	938	−46	−38	48	5.44
Precentral gyrus	L	6	84	−52	−6	46	5.00
Cuneus	R	23	268	12	−70	8	4.99
Medial frontal gyrus	L	8	111	−2	24	48	4.63
Posterior cingulate	L	30	171	−6	−68	8	4.15
Korean-Chinese > English-Chinese or Korean- English							
Cuneus	R	18	1522	18	−90	2	7.01
Cuneus	L	18	620	−24	−92	6	6.00
Inferior frontal gyrus	L	9	154	−48	4	34	5.14
Chinese-English > Korean-Chinese or Korean-English							
Inferior frontal gyrus	L	47	91	−38	24	0	4.60
Cuneus	L	18	195	−2	−80	2	3.76


Korean & English greater athan English & Chinese or Korean & Chinese

Korean & Chinese greater than English & Chinese or English & aaKorean

Chinese & English greater than Korean & Chinese or English & Korean

Fig. 3 Greater overlap in one pair of languages than other two pairs

Table 7 Brain activation for the contrast of rhyming minus baseline for group comparisons (EE, KK, and CC)

Anatomical Region	H	BA	Voxels	x	y	z	Z
English > Korean							
Middle occipital gyrus	L	19	1648	−44	−66	−10	6.82
Medial frontal gyrus	L	6	301	−6	14	52	5.77
Superior parietal lobule	L	7	1402	−28	−62	46	5.63
Inferior frontal gyrus	L	45	2052	−48	18	22	5.52
Cuneus	R	17	2053	16	−78	10	5.19
Precentral gyrus	L	6	230	−52	−6	50	4.62
Parahippocampal gyrus	R	34	66	22	−14	−18	4.56
Middle frontal gyrus	L	6	82	−22	−8	54	4.34
Superior temporal gyrus	L	22	115	−56	12	−2	4.19
Middle occipital gyrus	R	19	147	48	−76	0	4.16
Korean > English							
Middle frontal gyrus	R	9	752	26	28	40	5.36
Supramarginal gyrus	R	40	959	64	−48	24	5.16
Precuneus	L	19	703	−38	−76	36	5.12
Inferior parietal lobule	R	40	233	42	−72	38	4.94
Superior frontal gyrus	L	9	239	−16	56	34	4.62
Precuneus	L	7	387	−6	−70	36	4.41
Middle frontal gyrus	L	8	116	−28	30	46	4.35
Cingulate gyrus	R	31	449	8	−26	44	4.32
Middle frontal gyrus	L	9	130	−40	24	40	4.20
Anterior cingulate	L	32	57	−10	48	−2	4.11
Middle frontal gyrus	R	8	90	40	6	48	4.07
Precentral gyrus	R	13	89	48	16	8	3.99
English > Chinese							
Fusiform gyrus	L	37	1428	−48	−50	−20	6.74
Superior parietal lobule	L	7	1121	−28	−64	44	5.73
Inferior frontal gyrus	L	45/46	2217	−46	40	6	5.50
Medial frontal gyrus	L	8	188	−4	12	52	4.71
Lingual gyrus	R	18	699	12	−60	0	4.70
Superior temporal gyrus	L	22	165	−56	−40	8	4.67
Parahippocampal gyrus	R	34	60	22	−14	−18	4.41
Precentral gyrus	L	6	127	−42	−12	46	3.99
Chinese > English							
Superior frontal gyrus	R	8	291	24	28	42	5.26
Precuneus	L	19	156	−38	−74	36	4.78
Supramarginal gyrus	R	40	476	62	−48	24	4.61
Precuneus	L	31	189	−10	−58	30	4.41
Superior frontal gyrus	R	10	238	20	52	22	4.35
Inferior parietal lobule	R	40	183	42	−72	38	4.28
Middle frontal gyrus	L	9	52	−40	24	38	4.13
Cingulate gyrus	R	31	285	8	−26	44	4.08

Table 7 (continued)

Anatomical Region	H	BA	Voxels	x	y	z	Z
Middle frontal gyrus	L	8	110	−28	28	46	4.07
Superior frontal gyrus	L	10	167	−16	56	30	4.04
Supramarginal gyrus	L	40	63	−44	−54	22	3.95
Middle frontal gyrus	R	8	58	42	12	56	3.52
Korean > Chinese							
-							
Chinese > Korean							
Middle occipital gyrus	R	18	95	24	−92	2	4.76
Cuneus	L	18	97	−18	−96	−2	4.89

gyrus, precentral gyrus, right lingual gyrus, and parahippocampal gyrus. In contrast, Chinese produced greater activation than did English in the bilateral middle/superior frontal gyri, supramarginal gyri, left precuneus, right inferior parietal lobule, cingulate gyrus, and precentral gyrus.

Korean did not produce greater activation compared to Chinese. Instead, Chinese elicited greater activation in the right middle occipital gyrus and left cuneus.

Conjunction analyses

First, we conducted a conjunction analysis between English > Korean and English > Chinese to identify language-specific regions exhibiting greater activation in response to English compared to the other two languages. As shown in Table 8 and Fig. 5, compared to Korean and Chinese, English elicited greater activation in the left middle occipital gyri, superior parietal lobule, inferior frontal gyrus, medial frontal gyrus, superior temporal gyrus, posterior cingulate, precentral gyrus, and right parahippocampal gyrus. However, no regions demonstrated significant activation in the conjunction of Korean > English and Korean > Chinese or in the conjunction of Chinese > English and Chinese > Korean.

We conducted another set of conjunction analyses to identify brain regions that were more activated for two of the languages compared to the third. Korean and Chinese elicited greater activation than English in several common areas including the bilateral middle frontal gyri, inferior parietal lobule, left superior frontal gyrus, supramarginal gyrus, right cingulate gyrus, and precentral gyrus. English and Korean did not elicit greater activation compared to Chinese in any common regions (English > Chinese and Korean > Chinese). Additionally, the conjunction of English > Korean and Chinese > Korean revealed greater activation in the left cuneus for English and Chinese than for Korean.

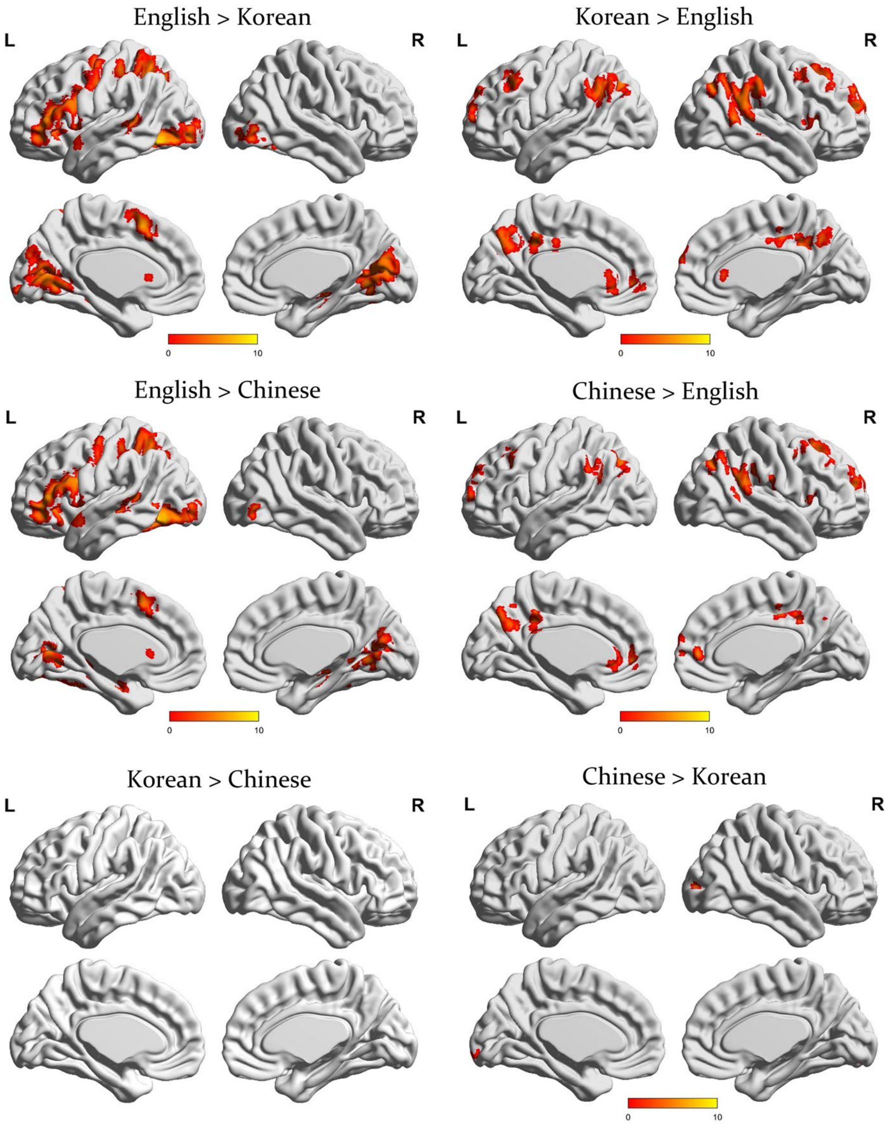


Fig. 4 Direct comparisons of languages

Discussion

We directly compared brain activation for three languages: English, Korean, and Chinese. These languages provide a unique opportunity to examine how language similarities and differences are represented in the brain. Korean shares alphabetic characteristics with English in mapping orthography to phonology, and it shares the nonlinear visual spatial layout in syllabic units with Chinese.

Table 8 Brain activation in conjunction analyses for each contrast

Anatomical Region	H	BA	Voxels	x	y	z	Z
English > Korean & English > Chinese							
Fusiform gyrus	L	19	1160	−44	−46	−16	7.05
Superior parietal lobule	L	7	1238	−28	−62	44	6.17
Inferior frontal gyrus	L	45/46	2278	−46	40	6	5.96
Medial frontal gyrus	L	8	267	−4	12	52	5.58
Superior temporal gyrus	L	22	210	−56	−40	8	5.12
Posterior cingulate	L	30	1555	−4	−70	8	5.08
Parahippocampal gyrus	R	34	69	22	−14	−18	4.73
Precentral gyrus	L	6	157	−52	−6	48	4.59
Korean > English & Korean > Chinese							
–							
Chinese > English & Chinese > Korean							
–							
English > Chinese & Korean > Chinese							
–							
Korean > English & Chinese > English							
Middle frontal gyrus	R	9	655	26	28	40	5.32
Precuneus	L	19	200	−38	−76	36	5.18
Inferior parietal lobule	R	40	534	64	−42	22	4.68
Middle frontal gyrus	L	9	74	−40	22	40	4.30
Precuneus	L	7	241	−8	−62	30	4.26
Cingulate gyrus	R	31	204	8	−26	44	4.20
Inferior parietal lobule	R	40	115	42	−72	38	4.18
Middle frontal gyrus	L	8	113	−24	28	46	4.16
Precentral gyrus	R	44	56	48	18	8	4.14
Superior frontal gyrus	L	9	131	−18	54	36	4.13
Supramarginal gyrus	L	40	67	−44	−52	38	3.97
Inferior parietal lobule	L	40	59	−64	−44	32	3.92
English > Korean & Chinese > Korean							
Cuneus	L	18	71	−20	−94	−2	4.05

In terms of behavioral performance, English and Korean elicited higher accuracies and faster reaction times than did Chinese. This presumably occurred because of the strong connection between orthography and phonology in alphabetic languages. Korean and English are alphabetic; hence, rhymes can be represented visually. However, Chinese characters are not phonemic, so rhymes must be abstractly segmented from the syllable. Therefore, the rhyming task is more difficult for Chinese speakers than for Korean and English speakers.

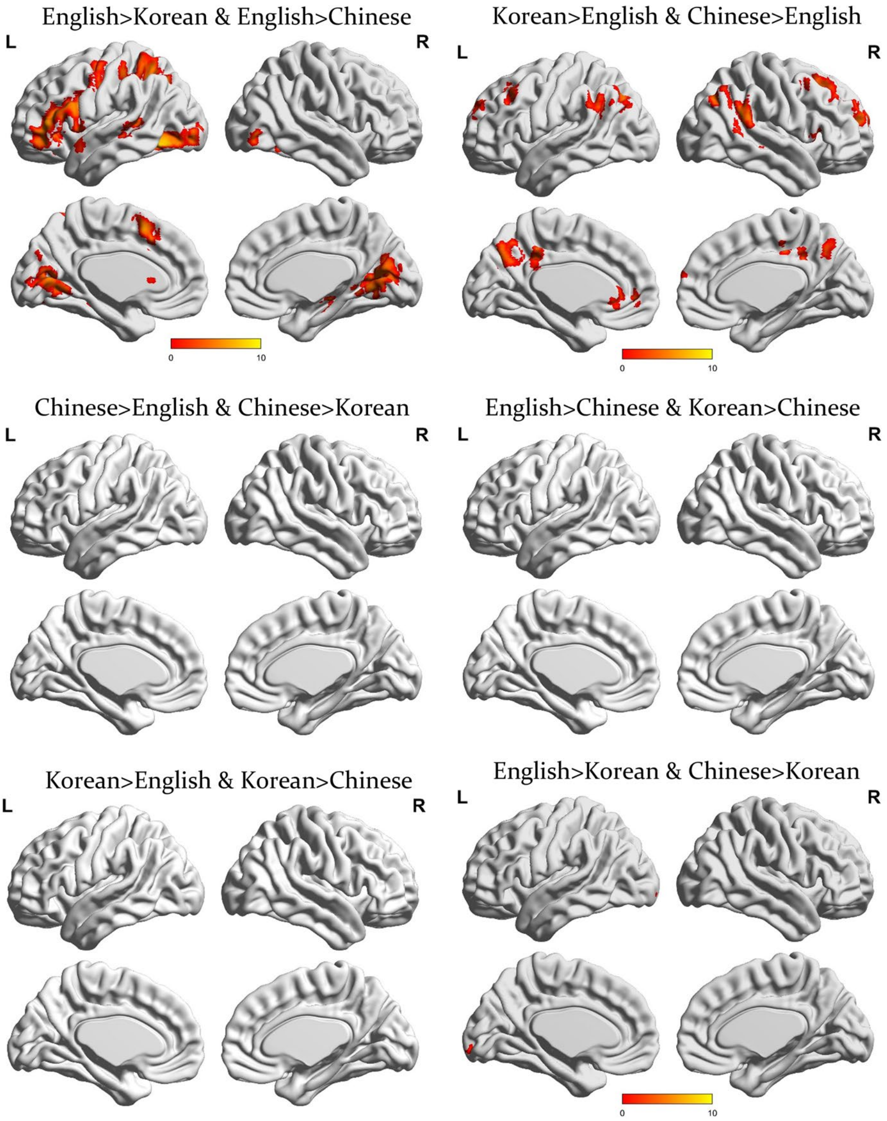


Fig. 5 Results of conjunction analyses of group comparisons

Commonality of brain activation across languages

Consistent with previous findings (Bolger et al., 2005; Tan et al., 2005), the typical reading network is activated in all three languages. Namely, we observed that the posterior occipitotemporal regions (i.e., bilateral middle occipital gyri), which are related to the primary demands of visual orthographic processing in reading (Perfetti et al., 2013), were activated for all three languages. Additionally, other shared regions such as the left inferior frontal gyrus and middle frontal gyrus are thought to be engaged in phonological retrieval and phonological manipulation, which our rhyming judgment task required. This suggests a universal reading network across languages, including visuo-orthographic regions and phonological mapping regions.

As for the overlap analysis, Korean and English overlapped in the inferior frontal gyrus, but we observed no such overlap between English and Chinese or between Korean and Chinese. This is consistent with the inferior frontal gyrus's significant role in alphabetic reading (Bolger et al., 2005). We also found overlap between Korean and Chinese in the right cuneus but not between Korean and English or between Chinese and English. This aligns with our hypothesis that Korean and Chinese share the complexity of visual forms and both involve the right visual spatial analysis region for the holistic visual configuration required by the square-like blocks of strokes. Korean and Chinese also showed overlap in the left middle frontal gyrus, but this was not the case for Korean and English or Chinese and English, suggesting that Korean shares syllable-level phonological retrieval with Chinese. In sum, Korean shares the alphabetic reading regions with English and shares the holistic visual-orthographic regions as well as syllable-level mapping regions with Chinese, thereby supporting our predictions.

Language differences

Our direct language comparisons revealed intriguing similarities between Korean and Chinese and idiosyncrasies of English. Particularly, English elicited greater activation than did Korean and Chinese in the left inferior frontal gyrus (toward pars triangularis), superior temporal gyrus, and left fusiform gyrus, while Korean and Chinese elicited greater activation than did English in the left middle frontal gyrus, inferior parietal lobule, and precuneus. This suggests that although Korean is alphabetic and behavioral performance for Korean is similar to that for English, it is more similar to Chinese than it is to English in the brain. The language differences that we found in the brain are consistent with previous comparisons between English and Chinese (Bolger, 2005; Tan, 2005). The left inferior frontal gyrus and superior temporal gyrus are more involved in English than in Chinese due to phoneme-level processing in English (Booth et al., 2006), potentially because these regions undertake mapping between fine-grained script units and their corresponding sound units (Bolger et al., 2005). The left inferior frontal gyrus is involved in lexical selection and integration, especially when there is inconsistency in the mapping between graphemes and phonemes (Bolger et al., 2008). The left superior temporal gyrus is involved in phonological assembly (Das et al., 2011; Jobard et al., 2003; Paulesu et al., 2000). In contrast, the left middle frontal gyrus and the left inferior parietal lobule are more involved in Chinese than in English due to addressed phonology. The left middle frontal gyrus might be related to the phonological processing of written Chinese (Tan et al., 2005), specifically dealing with lexical selection via addressed phonology (Bolger et al., 2005; Perfetti et al., 2013). The left inferior parietal lobule is more involved in Chinese than in English due to the direct retrieval of phonological information in Chinese characters, which contrasts with the segmental analysis in alphabetic systems (Tan et al., 2005).

These language differences in the brain accord with the dual-route model, according to which Chinese utilizes the lexical route in reading while English requires additional involvement of the sub-lexical route due to the alphabetic nature of script to sound mapping despite its opacity. Therefore, the addressed phonology regions in the left middle frontal gyrus and inferior parietal lobule are more involved in Chinese, while the phonological assembly region in the superior temporal gyrus and phoneme-level processing region in the inferior frontal gyrus are more involved in English. According to the dual-route model, Korean is a shallow orthography with regular mapping between graphemes and phonemes, and it should rely significantly on the sub-lexical route during reading. However, the Korean alphabet (Hangul) is packed into syllable blocks, which lead to saliency of syllable-level phonological processing. Therefore, the addressed phonology at the syllable level is more prominent in Korean. Studies have shown that syllables are the proximate unit in Korean (Verdonschot et al., 2021, but see also Li et al., 2021). Therefore, although Korean is alphabetic, it is similar to Chinese in its syllable-level phonological processing, eliciting greater activation in the left middle frontal gyrus and inferior parietal lobule compared to English. This pattern may also be attributed to the fact that Chinese and Korean words used in this study were disyllabic, whereas the English stimuli were monosyllabic. Overall, in the overlap analysis, Korean showed commonality with both English and Chinese; however, in the direct comparison, Korean showed greater similarity to Chinese than to English. These findings suggest that dual-route model should be applied in view of writing systems' other characteristics. For example, the script relativity hypothesis (Pae et al., 2020) has recently been proposed to explain language and cognitive processes collectively with an emphasis on script influence. Thus, the current findings from the three contrasting scripts provide direct neurolinguistic evidence for the script relativity hypothesis.

We found that the left fusiform gyrus is more involved in reading words in English than in Korean or Chinese (i.e., English > Korean and English > Chinese). The left fusiform gyrus is known as the visual word form area, which is strongly related to letter-selective response in orthographic recognition (Lochy et al., 2018). Previous studies have demonstrated some contrasting patterns in this region's activation between English and Chinese. Specifically, English tends to elicit left-dominant activation in this region, whereas Chinese activates the bilateral fusiform gyrus (Bolger et al., 2005; Cao et al., 2013; Tan et al., 2005). The left fusiform gyrus may be essential for configuring the left–right layout of letters rather than the squared symbols of Chinese and Korean. In contrast, Chinese and Korean elicited greater activation in the left precuneus than did English. The precuneus is associated with visual spatial analysis of characters, and it was found to be more involved in Chinese than in English in previous research (Cao et al., 2013; Kravitz et al., 2012; Perfetti et al., 2013). Besides linguistic differences, reading instructions are also very different in Chinese and English. Phonics and phonology are more emphasized in English reading, whereas handwriting and orthography are more emphasized in Chinese reading acquisition. As with Chinese, writing practice (copying) is generally emphasized in Korean reading acquisition. Indeed, research has found copying instructions to be more effective than other types of instructions (e.g., letter-based instructions) for early learners of Korean (Cho et al., 2020). These instructional differences during reading acquisition would influence how words are represented in the brain and explain why different regions are involved even in mature readers. Thus, on account of both brain regions involved in visual word form processing and those involved in phonological conversion, Korean is more similar to Chinese than it is to English. Lastly, Chinese also elicited greater activation in the right middle occipital gyrus than did Korean, which could be due to the greater visual complexity of Chinese characters compared to Korean Hangul (Cao et al., 2010; Tan et al., 2005).

Taken together, these findings based on a unique set of languages highlight that diversity in terms of writing systems and script variations is reflected in the shared and different brain networks among languages. Thus, our results contribute to a more comprehensive understanding of the reading brain by providing evidence of language-universal and language-specific networks.

Limitations

One limitation of this study lies in the language backgrounds of participants in the three language groups. As Korean participants were living in China at the time of the study, they had learned both English and Chinese as their second languages and were exposed to the latter regularly. Although most other participants in the English and Chinese groups were also bilingual, their second-language learning experience might not have been as salient as that for the Korean participants. As it is possible that experiences learning additional languages could affect the first-language reading network (Tu et al., 2015), greater similarities in brain activation between Korean and Chinese might be due to the extensive experience of learning Chinese among our Korean participants.

Conclusion

We found that Korean overlapped with English in the alphabetic reading regions, and it overlapped with Chinese in the holistic visual orthographic regions and the syllable-level phonological retrieval region. This is consistent with the fact that Korean shares its alphabetic nature with English and shares the complex visual forms and the emphasis on the syllable in phonology with Chinese. However, when we directly compared the languages, we found that Korean was more similar to Chinese than to English, which was rather surprising. It suggests that the similarity between Korean and Chinese in their written form and the special emphasis on syllables (i.e., alphabetic syllabary and morpho-syllabic) seems to be more influential in brain activation than is their alphabetic nature. We regard our findings as novel in the understanding of the potential roles of writing systems and/or script characteristics in activating relevant brain regions.

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