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Early MEG markers for reading Chinese phonograms: Evidence from radical combinability and consistency effects

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ABSTRACT

Studies using functional magnetic resonance imaging have indicated that activities in the left inferior frontal cortex and left temporoparietal regions are associated with orthographic neighborhood size. To elucidate the temporal dynamics of reading-related cortical activities, we manipulated two types of neighborhood properties for Chinese phonograms, phonetic combinability and consistency. By using source analysis techniques in combination with magnetoencephalography, the results demonstrated a combinability effect in the right fusiform gyrus at ~170 ms, which may reflect perceptual expertise in processing Chinese orthography. During 200 ms to 250 ms, the left anterior insula showed larger activity in reading small combinability characters than in reading large combinability characters, and the left inferior parietal cortex showed greater activity in reading low consistency characters than in reading high consistency characters. These results indicate that the left anterior insula cortex and left inferior parietal cortex may play important roles in the early stages of reading Chinese phonograms.

1. Introduction

Studies on visual word recognition have indicated that properties of orthographically similar words substantially affect word recognition. In alphabetic languages, orthographic similarity has been operationalized as the subset of words that share all but one letter with a target word. This set of words is referred to as the “orthographic neighborhood” of the target word (Coltheart et al., 1977). For example, the neighbors of “cheat” are any words that can be created by changing a single letter of a word while preserving letter positions (e.g., “cheap,” “chest,” “cleat,” and “wheat”). Many studies have investigated effects of orthographic neighborhood size, revealing a facilitative effect of neighborhood size for reading low-frequency words in a lexical decision task (Andrews, 1989; Forster & Shen, 1996; Pollatsek, Perea, & Binder, 1999). That is, reading low-frequency words with many neighbors tends to exhibit shorter response latency than does reading words with few neighbors, while the neighborhood size effect is negligible or nonexistent for high-frequency words. In addition, inhibitory effects of neighborhood size and neighborhood frequency have been reported in studies using tasks that involve identifying words, such as perceptual identification tasks and the progressive demasking paradigm (Grainger & Segui, 1990; Perea, Carreiras, & Grainger, 2004; Pollatsek et al., 1999; Snodgrass & Mintzer, 1993).

To reconcile the inhibitory and facilitative effects of neighborhood properties, Grainger and Jacobs (1996) hypothesized two intra-lexical sources in the multiple read-out model (MROM) that can generate a “yes” response in the lexical decision task: (1) global activation in the orthographic lexicon induced by the partial activation of orthographic neighbors of the target word, and (2) local activation in the representational unit of the presented word. These concepts originated from the work of McClelland and Rumelhart (1981), who stated that an input of a string of letters would activate a set of orthographically similar words in the lexicon, and that there are inhibitory links between the intra-lexical word units. According to MROM, either global or local activation that exceeds a given criterion would generate a “word” response, and the task demand would determine the major source for the generation of that response. Therefore, reading a word with many neighbors would trigger a large activation in the lexical system, producing a fast positive response. Conversely, when participants are asked to correctly identify the target words, the positive response would be triggered mostly by local activation, which is substantially affected by lateral inhibition. Therefore, reading words with many orthographic neighbors or with high-frequency

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neighbors might be prolonged due to the lateral inhibition between the lexical units in tasks requiring correct identification.

Studies using functional magnetic resonance imaging (fMRI) have demonstrated neural correlates indicative of neighborhood size effects. For example, Binder et al. (2003) reported that words without neighbors elicited greater activation than words with neighbors in a left hemisphere network, including the left middle frontal gyri, the left superior frontal gyri, the left angular gyrus, and the left middle temporal gyrus, which were previously associated with semantic processing. However, this finding seems to result from the task's emphasis on response accuracy. Consistent with this, Fiebach, Ricker, Friederici, and Jacobs (2007) manipulated the orthographic neighborhood size of real words and pseudowords without stressing the need for speed or accuracy, and did not observe a significant effect of neighborhood size on the activation of the left temporal lobe. In addition, they demonstrated a lexicality-by-neighborhood size interaction in frontal regions associated with executive control functions. That is, both mid-dorsolateral and medial prefrontal cortex showed deactivation in response to words with many neighbors, and these regions showed large activation in response to pseudowords with many neighbors. MROM assumes that the "non-word" response is generated after the inhibitory links inhibit the tendency to make a positive response, so reading non-words with many neighbors would generally result in longer response times than reading non-words with few neighbors. Therefore, Fiebach et al. (2007) argue that the finding of a lexicality-by-neighborhood size interaction in the fMRI data might be unrelated to the fast/early mechanism of MROM.

However, the poor temporal resolution of fMRI may prevent detection of the neural correlates of the early pre-lexical mechanism in MROM. Recent event-related potential (ERP) evidence obtained across writing systems has suggested that the properties of orthographic neighbors substantially shape ERP components that could index mechanisms hypothesized by MROM (Holcomb, Grainger, & O'Rourke, 2002; Hsu, Tsai, Lee, & Tzeng, 2009). For example, Holcomb, Grainger, and O'Rourke (2002) demonstrated that words with small neighborhood size elicited larger amplitude in P200 than words with large neighborhood size did, and reading words with large neighborhood size elicited larger amplitude in N400 than reading words with small neighborhood size. Similar results have been demonstrated in studies of reading disyllabic words in Spanish, French and Basque (Barber, Vergara, & Carreiras, 2004; Chetail, Colin, & Content, 2012; Vergara-Martinez, Dunabeitia, Laka, & Carreiras, 2009), and in reading Chinese characters (Hsu et al., 2009; Kong et al., 2010; Lee et al., 2007; Su, Mak, Cheung, & Law, 2012; Wu, Mo, Tsang, & Chen, 2012). In summary, these findings imply that the P200 might be associated with the early activation of orthographically/phonologically similar words in the sublexical process.

Research on Chinese character recognition has used source analysis techniques, such as the Laplacian weighted minimum norm procedure, to estimate neural generators of ERP activities in reading Chinese characters. However, the neural generators of P200 is disputed, as previous studies have conflicting results. Hsiao, Shillcock, and Lee (2007) suggested the N170/P200 activity over the anterior regions reflects volume-conducted activity originally generated in the occipitotemporal regions which generated the N170 activity (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Maurer, Brandeis, & McCandliss, 2005). However, with the same source analysis techniques, Liu and Perfetti (2003) found that activities in occipital regions and precentral areas (BA 6/8) contributed to P200. Finally, Liu, Perfetti, and Hart (2003) only found activity of right BA 6/8 at ∼200 ms. Thus, it remains unclear whether reading-related brain activities at ∼200 ms are supported by a homogenous generator (e.g., the bilateral occipitotemporal regions) or by several regions across the brain.

This study aims to elucidate the neural correlates of Chinese orthography-to-phonology transformation at ∼200 ms by manipulating two properties of radical-level information—phonetic consistency and combinability—of Chinese phonograms. In Chinese, approximately 80% of the characters are phonograms that consist of a semantic radical (usually on the left-hand side) and a phonetic radical (usually on the right-hand side). The semantic radical may provide information on character's meaning, while the phonetic radical may provide information for character's pronunciation. Lee, Tsai, Su, Tzeng, and Hung (2005) estimated the phonetic consistency of Chinese phonograms by calculating the ratio of the number of characters with only the same pronunciation and the same phonetic radical to the number of characters with the same phonetic radical. The findings of phonetic consistency effects in reading Chinese characters (Lee et al., 2005; Yang, McCandliss, Shu, & Zevin, 2009) corroborate earlier findings in reading English words (Jared, 1997, 2002). That is, in reading words or characters aloud, stimuli with high consistency triggered faster responses than stimuli with low consistency.

In addition, to address the orthographic neighborhood size effect in reading Chinese characters, studies have investigated radical combinability, defined as the number of characters sharing the same radical (Chen & Weekes, 2004; Feldman & Siok, 1997, 1999; Hsiao, Shillcock, & Lavidor, 2006; Hsu et al., 2009). Radical combinability can be further divided into phonetic combinability and semantic combinability, which are defined as the number of phonograms that share the same phonetic or semantic radical, respectively. Parallel to the effect of orthographic neighborhood size (Andrews, 1989, 1992, 1997), many studies have demonstrated the facilitative combinability effect for both variables—characters with large combinability revealed a faster response latency in the character decision task than characters with small combinability (Chen & Weekes, 2004; Feldman & Siok, 1997, 1999; Hsiao et al., 2006; Wu et al., 2012). Hsu et al. (2009) used ERP measurements to examine different processing of radical-level information by manipulating phonetic combinability and consistency. Their results indicated that the bilateral N170 activity is larger in reading large combinability characters than in reading small combinability characters, which might reflect the perceptual proficiency of processing word-forms. Furthermore, characters with either small combinability or low consistency revealed a larger P200 activity than those with large combinability or high consistency, which might reflect the extraction of orthographic and phonological knowledge of phonograms. These findings suggest that framework of MROM could account for processing Chinese orthography. Specifically, reading large combinability characters entails large global activation and yields a fast response.

Although the excellent temporal resolution of ERP allows one to examine various stages of cognitive processes in different time windows, the volume conduction poses a challenge to identify the source. In contrast, magnetoencephalography (MEG) measures the magnetic field which is not influenced by the conductivities of the scalp and the brain tissue and thus is an ideal tool to investigate the neural generated underpinning of visual word recognition on a millisecond basis (Dale et al., 2000). Hsu, Lee, and Marantz (2011) used a single-trial analysis method to investigate the relationships between the estimated source activities of the MEG data and a variety of lexical variables while participants made lexical decisions. They demonstrated that the activation in the right fusiform gyrus at ∼170 ms was associated with radical combinability and that the left fusiform gyrus at ∼170 ms was associated with the number of strokes. However, their analysis did not include phonetic consistency, and the ventral occipitotemporal cortex was the sole the region of interest.

This study aimed to clarify whether effects of phonetic combinability and consistency are present in the brain at 250 ms by using the same paradigm and the same stimuli as Hsu et al. (2009) but with MEG. The major point of interest is the timing of phonetic combinability and consistency effects unfold in different brain regions, as previous ERP studies have demonstrated the relationship between P200 and the early mechanism of MROM. Previous fMRI studies using covert naming tasks have demonstrated effects of phonetic consistency in a range of brain regions, including the left inferior frontal gyrus, left inferior parietal gyrus, left supramarginal gyrus, and left occipitotemporal regions (Lee, Huang, Kuo, Tsai, & Tzeng, 2010; Lee et al., 2004). In addition, Yang, Wang, Shu, and Zevin (2011) argued that several reading-related brain regions play different roles in reading Chinese characters. Specifically, the left temporoparietal cortex appeared to be involved in processing sublexical units of Chinese characters (i.e., in mapping among orthography and phonology), while task difficulty was related to activities in a large network, including ventral occipitotemporal, inferior frontal cortices, middle frontal, and insula cortices. These findings are consistent with studies involving the reading of alphabetic words (Bolger, Hornickel, Cone, Burman, & Booth, 2008; Cattinelli, Borghese, Gallucci, & Paulesu, 2013; Fiez, Balota, Raichle, & Petersen, 1999).

We hypothesize that if there is a network across cortical regions that promote orthography-to-phonology transformation at 250 ms, the results may demonstrate effects of consistency and combinability in reading-related networks, as indicated by fMRI studies. In addition, an fMRI study of Spanish language processing demonstrated that activity in the left anterior insula was enhanced in reading words with low syllable frequency (Carreiras, Mechelli, & Price, 2006), suggesting that the left anterior insula may be a possible location of a combinability effect. In addition, Hsu et al. (2009) found greater bilateral N170 activity when reading characters with large combinability than when reading characters with small combinability. This combinability effect on N170 might reflect perceptual expertise in processing word-forms (Dehaene, Cohen, Sigman, & Vinckier, 2005). It remains to be seen whether phonetic consistency and combinability effects might be associated with separate brain regions in different time windows.

2. Materials and methods

2.1. Design and stimuli

Fourteen right-handed native Chinese speakers with normal to corrected vision participated in this study. All participants were male college students. The current study was approved by the Human Subject Research Ethics Committee/IRB of Academia Sinica, Taiwan. Written consent forms were obtained from all participants. Target characters were a list of 120 Chinese phonograms selected from the Academia Sinica Balanced Corpus (Huang & Chen, 1998). The corpus is based on more than 5 million words (approximately 10 million characters). Each target character was configured horizontally with a semantic radical on the left and a phonetic radical on the right, which is the most typical structure of phonograms. Applying this selection rule avoided any effect of the position of the phonetic radical (Hsiao & Liu, 2010; Hsiao et al., 2007). These phonograms were divided into four categories by manipulating their phonological consistency (high vs. low) and phonetic combinability (large vs. small). The indices for phonetic combinability and consistency were calculated based on 3697 phonograms described in Hsu et al. (2009). Table 1 illustrates the characteristics of each condition. Each target character was paired with two probe characters matched by the number of strokes and character frequency, one of the probe characters having the same pronunciation as the corresponding target.

2.2. Experimental procedure

Participants laid in a magnetically shielded room. Each participant was given 30 practice trials and 120 randomized experimental trials in four test sessions. Participants were permitted to take breaks between test sessions. Fig. 1 shows the schematics of a trial. The trial began with the presentation of two vertical lines, one above and the other below the center of the screen, which were simultaneously presented for 500 ms. A target character was then presented in the center of the screen, between the two lines, for another 150 ms. Participants were asked to maintain their fixation at the mid-point between the two lines and silently name the target characters. The two lines and target character were then replaced with a cross at the center of the screen for 850 ms. Next, two probe characters were presented simultaneously on the right and left sides of the cross. After silently reading the target presented on the screen, participants were instructed to press the left button on a response pad with their left index finger when the pronunciation of the left probe character matched the target, and to press the right button on a response pad with their right index finger when the right probe character matched the target. The position of probe characters was counterbalanced among articipants. After pressing a button, or after 2000 ms without responding, a blank screen was presented for 1600 ms to allow the participants to blink if necessary. The aim of this task was to ensure that participants knew correct pronunciations of the target characters while processing the phonology of targets without a covert naming response that might cause muscular noise during the MEG recording. MEG data analyses were focused on time period relative to the onset of targets (Section 2.3.1). The mean correctness of all the participants was 93% (ranging from 84% to 99%).

MEG data were recorded continuously throughout the task by a 157-channel axial gradiometer whole-head MEG system (Yokogawa Electric Corporation, Japan) with a sampling frequency of 1 kHz. A band-pass filter (0.3–100 Hz) was applied during the recording. Prior to MEG acquisition, each participant's head shape

Table 1
Means and standard deviations of parameters for stimuli in the homophone judgment task.

Conditions	High consistency		Low consistency	
	Large combinability	Small combinability	Large combinability	Small combinability
Consistency	0.9 (0.11)	0.98 (0.07)	0.21 (0.09)	0.3 (0.09)
Phonetic combinability	9.8 (3.22)	3.2 (0.70)	11.37 (2.68)	3.63 (0.96)
Number of strokes	13.63 (3.66)	15.2 (3.98)	13.47 (4.28)	14.37 (4.73)
Frequency	32.37 (24.33)	31.7 (22.84)	32.53 (23.68)	34.63 (25.18)
Semantic combinability	85.1 (56.04)	81.13 (46.60)	75.73 (51.85)	76.23 (52.47)

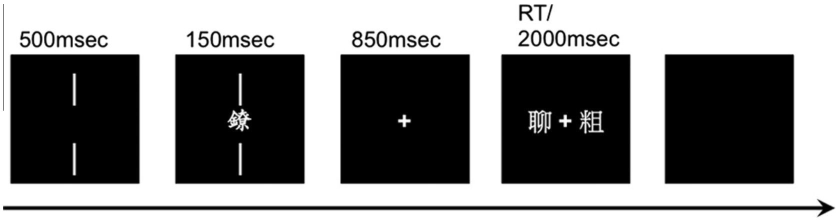

Fig. 1. Schematic of the trial.

was digitized, and head position indicator coils were used to localize the position of the participant's head inside the MEG helmet. The head-shape digitization and head position indicator locations were later used to co-register the MEG coordinate system to that of each participant's structural MR images.

2.3. Analysis methods

2.3.1. MEG preprocessing and minimum-norm estimation

In offline processing, MEG data were first noise-reduced using the time-shift PCA algorithm (de Cheveigné & Simon, 2007). The continuous MEG data were then divided into epochs with a 100 ms pre-stimulus interval and an 800 ms post-stimulus interval, and baseline corrected using the pre-stimulus data. Trials with amplitude variations larger than 1.5 pT were excluded from averaging and subsequent statistical analyses. Each participant's MEG data was then averaged and low-pass filtered at 40 Hz.

The participants' structural MR images were processed in FreeSurfer (CorTechs Labs, La Jolla, CA and MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA) to create a cortical reconstruction of each brain. The MNE toolbox (MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA) was then used to calculate a cortically constrained L2 minimum-norm solution for each participant's MEG data with 5124 sources on each participant's cortical surface (Dale et al., 2000). The boundary element model method was used to compute the forward solution, which estimates the resulting magnetic field at each MEG sensor according to the activity at each of the 5124 sources. This forward solution was then employed to create the inverse solution, which identified the spatiotemporal distribution of activity over sources that best account for each participant's average MEG data. Only components of activation that were in the direction normal to the cortical surface were retained in the minimum-norm solution, and the resulting minimum-norm estimates were converted into a dynamic statistical parameter map (dSPM), which measures the noise-normalized activation at each source to avoid some of the inaccuracies of standard minimum-norm calculations.

2.3.2. Regions of interests (ROIs) and statistical analysis

The following ROI analyses adopt a novel method derived from previous studies (Hsu et al., 2011; Lewis, Solomyak, & Marantz, 2011; Simon, Lewis, & Marantz, 2012; Solomyak & Marantz, 2010). Each participant's cortical surface was normalized onto a standard brain supported by FreeSurfer, and then all participants' dSPM solutions were averaged for use in defining regions and time windows of interest. ROIs were selected based on peaks in the grand average dSPM over all trials and subjects. The dSPM solutions presented activation regions above the significant level relative to baseline noise estimates (Dale et al., 2000). Because this study focused on potential generators at 250 ms, ROIs were manually selected based on the grand-averaged dSPM maps by labeling cortical regions with dSPM values larger than 2.6 (corresponding to $p < .05$ before multiple comparison correction) between 150–300 ms post-stimulus onset. This threshold allows increased sensitivity for effects presented in a shorter time window without affecting the false alarm rate of the non-parametric statistical test (Maris & Oostenveld, 2007). The times between 150 and 300 ms were chosen to span a window within which effects have been associated with processing sublexical orthography and phonology, as reported in the electrophysiology literature (e.g. Chetail et al., 2012). Next, the response latency for the ROIs was defined as the latency with the largest dSPM values, and we employed the Desikan–Killiany gyral atlas (Desikan et al., 2006) to identify the anatomical location for each ROIs.

An inverse solution was then used to compute the trial-by-trial minimum-norm estimation over each subject's raw MEG data for each identified ROIs at each time point. The resulting minimum-norm estimates were converted into dSPM values for subsequent analyses. The dependent variable was defined by averaging dSPM values over a 20-ms window centered at the response latency for each ROI based on the single-trial data. The amplitude was analyzed by separately applying a linear mixed model (LMM) over the single-trial data, with participants and items as crossed random effect. For fixed effects, consistency (high/low) and phonetic combinability (large/small) effects were coded as +.5/−.5 contrasts. The interaction between consistency and combinability was treated as a fixed effect. Traditionally, psycholinguists and cognitive psychologists have used analysis of variance (ANOVA) to estimate the effects of treatments, and have computed F-statistics by measuring the variation around the means from participants or items separately. In this regard, LMM analysis over the single-trial data has some advantages. First, multiple random variables can be included simultaneously. Second, parameter estimates are fitted by a restricted maximum likelihood criterion, which is not biased to the means of participants or items. Therefore, LMM analysis can handle unbalanced data sets and missing observations. Third, F-statistics assume that variance of treatments is homogenous (the *sphericity assumption*), an assumption that is always violated in neurophysiological measurements. Bagiella, Sloan, and Heitjan (2000) have demonstrated that LMM analysis can provide more conservative results than F-statistics when the data is non-spherical. Finally, as Baayen et al. (2008) have argued, LMM analysis makes fewer incorrect rejections of a true null hypothesis (i.e., the Type I error) and is less biased by number of observations than F-statistics.

The LMM analysis was done by using the lmer program of the lme4 package (Baayen et al., 2008; Bates and Sarkar, 2007). To evaluate the significance of each fixed effect, we employed the pvals.fnc program of the languageR package to perform a Markov Chain Monte Carlo simulation, using 1000 simulations to obtain the *p* values. These packages are supplied in the R system for statistical computing (R Development Core Team, 2009).

3. Results

3.1. ROIs and peak latency

Fig. 2 shows ROIs in the grand-averaged dSPM maps. After character onset, the left pericalcarine cortex showed the earliest

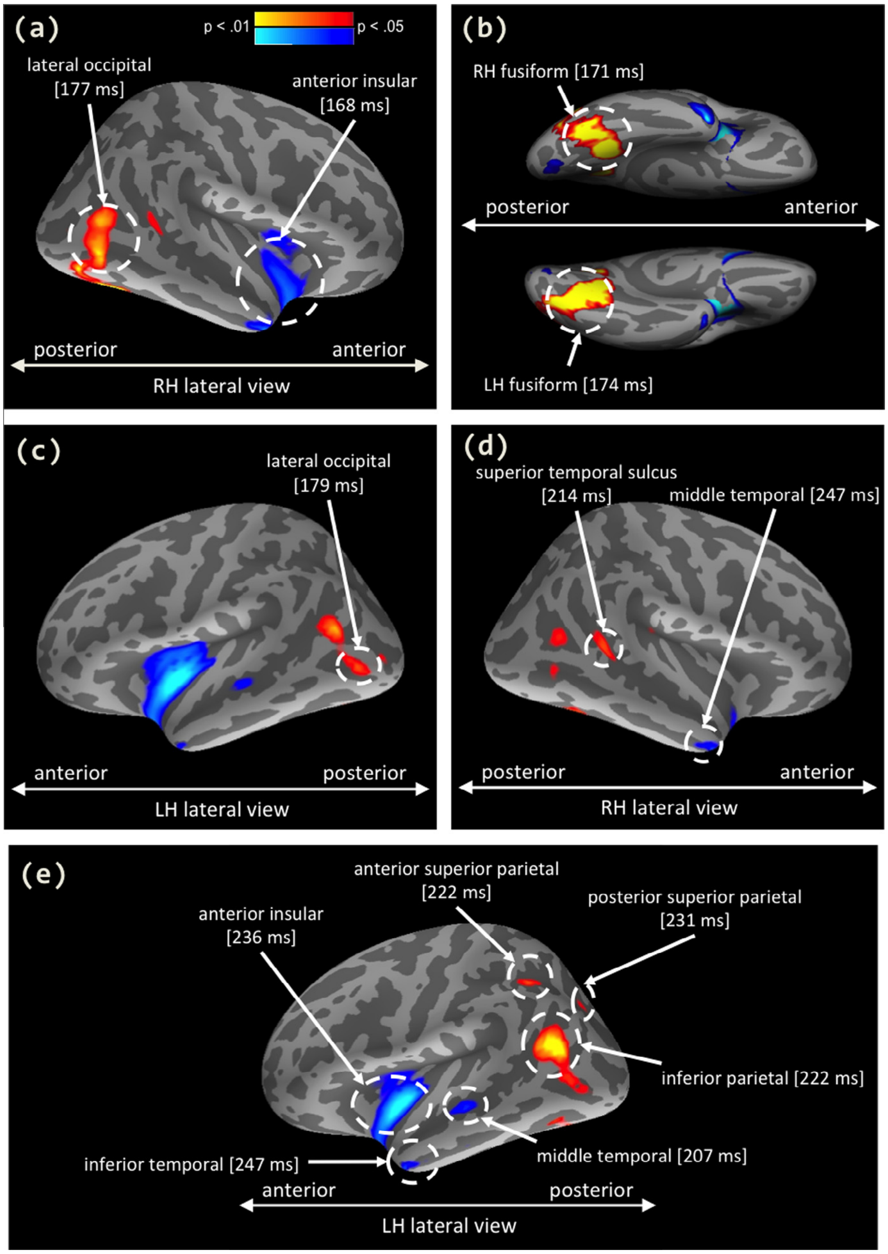

Fig. 2. dSPM maps for grand averaged activation. ROIs are marked by white circles. RH: right hemisphere; LH: left hemisphere.

activation in the form of a positive (outward flowing current) activation peaking at 107 ms, which was followed by a positive activation in the right pericalcarine cortex peaking at 135 ms, and a negative (inward flowing current) activation in right insular cortex peaking at 168 ms (Fig. 2a). Subsequently, both right and left fusiform cortices showed positive activations that peaked at 171 ms and 174 ms, respectively (Fig. 2b). The right lateral occipital cortex and left lateral occipital cortex showed positive activations peaking at 177 ms (Fig. 2a) and 179 ms (Fig. 2c), respectively. After 200 ms, activity spread in two sub-regions in the right temporal cortex (Fig. 2d) and many regions in the left hemisphere (2e). In the left hemisphere, five regions showed activity after 200 ms, including the middle temporal cortex (negative activation peaking at 207 ms), inferior parietal cortex (positive activation peaking at 222 ms), anterior superior parietal cortex (positive activation peaking at 222 ms), posterior superior parietal cortex (positive activation peaking at 231 ms), anterior insular cortex (negative activation peaking at 236 ms), and inferior temporal cortex (negative activation peaking at 247 ms). In the right hemisphere, two brain regions showed activity after 200 ms (Fig. 2d), including the posterior areas of the superior-temporal sulcus (positive activation peaking at 214 ms), and the anterior regions of the middle-temporal cortex (negative activation peaking at 247 ms).

3.2. Results of LMM analyses

Table 2 shows the results of main effects and the interaction in each ROI. Significant results are illustrated in Fig. 3 and are described as follows. The activation in the right fusiform cortex at ~170 ms yielded a significant effect of combinability ($b = .103$, $SE = .039$, $t = 2.6$, $p < .05$). The result indicates that characters with large phonetic combinability were associated with stronger activation in the right fusiform cortex. The activation in the left inferior parietal cortex at ~220 ms showed a significant effect of consistency ($b = -.11$, $SE = .041$, $t = -2.67$, $p < .05$), which indicated that characters with low consistency were associated with

Table 2
Summary of ROIs and the LMM analysis. Text in bold font denotes ROIs with significant effects of estimators. RH: right hemisphere; LH: left hemisphere.

ROI	Latency (ms)	*t*-Values			Talairach coordinates
		Consistency	Combinability	Interaction	
RH, insula	168	1.235	.668	1.21	37, 0, −15
RH, fusiform	171	.324	**2.6***	.582	**28, −55, −9**
LH, fusiform	174	1.33	−.06	−1.459	−30, −66, −3
RH, lateral-occipital	177	−.218	−.426	−.213	42, −65, 8
LH, lateral-occipital	197	.367	−.074	.562	−38, −71, 5
LH, middle-temporal	207	.868	1.065	1.329	−47, −26, −7
RH, superior-temporal sulcus	214	−.831	−.368	−.482	44, −43, 11
LH, inferior-parietal	222	**−2.678***	−.337	−.319	**−38, −58, 18**
LH, superior-parietal	222	−.736	.778	−1.732	−31, −46, 33
LH, superior-parietal	231	.407	.218	.345	−25, −62, 27
LH, insula	236	1.177	**2.523***	.456	**−35, −14, −5**
RH, middle-temporal	247	.341	1.523	1.167	43, 3, -29
LH, inferior-temporal	247	−.282	−.135	−.714	−41, −1, −30

* $p < 0.05$.

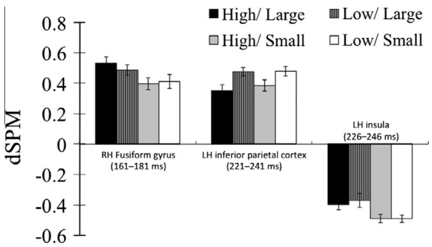

Fig. 3. Bar plots of mean dSPM activation within ROIs having significant effects of estimators.

stronger activation in the left inferior parietal cortex. Finally, the activation in the left anterior insular cortex at ~230 ms showed a significant effect of combinability ($b = .111$, $SE = .044$, $t = 2.52$, $p < .05$), indicating that characters with small phonetic combinability were associated with stronger activation in the left anterior insular cortex. The interaction of consistency and combinability was not significant in any ROI.

4. Discussion

This MEG study aimed to investigate the brain network underlying early stage of silent reading of Chinese phonograms to achieve a better understanding of the early mechanism hypothesized by MROM. The grand-average dSPM maps revealed activity of the bilateral fusiform gyrus at ~170 ms for naming Chinese characters. The finding is congruent with the general results in brain imaging studies of reading Chinese characters or Japanese Kanji—reading characters/Kanji has been shown to elicit activation in bilateral fusiform gyrus (Bolger et al., 2008; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005; Yang et al., 2011). In addition, an MEG study has demonstrated that bilateral fusiform cortices contributed to M170 responses in reading Chinese characters (Hsu et al., 2011). These results suggest that reading Chinese characters involves early perceptual analysis performed by the left and right fusiform gyrus. Regarding activities from 200 ms to 250 ms, reading Chinese characters involved a left-lateralized brain network, including the left middle temporal cortex, the left inferior parietal cortex, the left anterior insular cortex, the left superior parietal cortex, and the left inferior temporal cortex. The brain activities in this interval might be related to the P200 activity in ERP studies (Manuel Carreiras, Vergara, & Barber, 2005; Hsu et al., 2009). Although it remains unclear whether different generators support the P200 and N170 activities in the ERP literature, our data suggest that the source location based on MEG data could be distributed among several neural generators that might be related to ERP/MEG components from 170 ms to 250 ms.

The ROI analyses aimed to examine how these three regions, right fusiform, left anterior insula, and the left inferior parietal cortices, contribute to sublexical orthographic and phonological processing in early stages of reading Chinese phonograms. The earliest effect of the orthographic neighborhood size of the phonetic radical was shown in the activity in the right fusiform gyrus at 170 ms. Then, between 200 ms and 250 ms, orthographic neighborhood properties affected the activity in two brain regions—the left anterior insular cortex and the left inferior parietal cortex. The findings of neighborhood effects in these regions are not incidental, as previous brain imaging studies have indicated that their putative functions might be associated with the processing of sublexical orthography and phonology. For example, studies of reading English words and Chinese characters have suggested that (1) ventral occipitotemporal regions are the first neuronal station to which visual information is routed after early visual processing; (2) left inferior frontal and left insula are sensitive to effects of processing difficulty, such as word frequency and lexicality effects; and (3) left inferior parietal regions contribute to processing of orthography-to-phonology transformation, either via the grapheme-to-phoneme conversion roles in reading English words or via statistical relationships between phonetic radicals and pronunciations in reading Chinese characters (Cattinelli et al., 2013; Yang et al., 2011). In what follows, we discuss the functional implications of observed activity in these three regions.

Unlike Hsu et al. (2011), who used a single-trial regression approach to look for the relationship among a set of lexical properties and brain activity in certain region, the present study examined phonetic combinability effects by using a factorial design. The observed effect of phonetic combinability in the right fusiform gyrus at 170 ms might be associated with perceptual expertise in studies of visual word recognition. Previous ERP/MEG studies have indicated a positive correlation between the amplitude of N170/M170 and the perceptual expertise of visual word form. Specifically, it has been demonstrated that that reading letter strings elicited a larger N170 activity than reading strings of symbols (Bentin et al., 1999; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). In terms of radical combinability in Chinese characters, a radical with large combinability might emerge as a typical form at the sublexical level. Therefore, we speculate that the large activity in the right fusiform gyrus seen when reading large combinability characters might reflect a greater activation at the perceptual level than what is evoked when reading low combinability characters.

It is worth noting that the right-hemisphere lateralization of radical combinability effects in M170 might be also associated with two assumptions drawn from studies of word recognition. First, previous MEG studies indicated that the subtle influences of sublexical constituents in M170 might reflect the decomposition of words into stems and affixes (Solomyak & Marantz, 2010), or decomposition of characters into radicals (Hsu et al., 2011). We suspect that decomposing characters might be a crucial role of the right fusiform gyrus when reading Chinese characters. Secondly, the right-hemisphere lateralization of radical combinability effects might be related to the information distribution of the two sides of the characters (Hsiao, 2011; Hsiao & Liu, 2010; Hsiao et al., 2006). This suggests that characters with a large phonetic radical combinability have a less skewed information distribution as compared with those with a small combinability. Thus, participants may pay more attention to the semantic radical on the left for characters with a large phonetic radical combinability than for those with a small combinability, leading to increased activation/response amplitude in the right visual area. Nevertheless, both assumptions indicate a tremendous influence of sublexical units of Chinese orthography in early activity of right fusiform gyrus.

Most importantly, our results demonstrate effects of phonetic combinability and consistency in the left anterior insula cortex and the left inferior parietal cortex between 200 and 250 ms, respectively. Previous ERP studies have demonstrated the consistency and combinability effect on P200 (Hsu et al., 2009; Lee et al., 2007; Wu et al., 2012). The timing of these effects on P200 and the activities were found in the left anterior insular cortex and the left inferior parietal cortex, which suggests these regions might be associated with the fast/early mechanism in the MROM model. In other words, there might exist two sources for the early/fast component hypothesized by MROM—one is the left anterior insula cortex, which is associated with partial activation across orthographically similar words, and the other source is the left inferior parietal cortex, which is associated with partial activation of orthographically and phonologically similar words.

Previous behavioral studies have demonstrated a facilitatory effect of radical combinability in reading Chinese characters (Feldman & Siok, 1997, 1999; Hsiao et al., 2006). Brain imaging studies have indicated that activity of the left anterior insula is positively correlated with the task difficulty and the loading of phonological working memory (Downar, Crawley, Mikulis, & Davis, 2001; Kurth, Zilles, Fox, Laird, & Eickhoff, 2010). Although whether the insula mediates the core phonological and combinatory computation is still in debate, the present finding of the phonetic combinability effect in the left anterior insular cortex at $\sim$200 ms might reflect facilitative processing in reading large combinability characters. Our finding of early activity in the left anterior insular cortex is apparently consistent with findings of several ERP and fMRI studies on the effect of the first syllable frequency when reading disyllabic Spanish words. For example, Barber et al. (2004) demonstrated that word frequency only influenced the amplitude of N400, and that there was a facilitatory effect of first syllable frequency on P200. Using fMRI, Carreiras et al. (2006) also demonstrated a small left anterior insula activation when reading words with a high-frequency syllable, reflecting a facilitatory effect in reading words with high syllable frequency. In summary, the facilitatory effect in the left anterior insular cortex indicates that MROM model and the region that are linked. According to MROM, large combinability (more orthographic neighbors) facilitates character processing at the orthographic level due to larger orthographic activation, consequently demonstrating less activity in the left anterior insula, which is related to processing difficulty of word recognition.

The combinability effects found in the left anterior insular cortex and left inferior parietal can be incorporated into Yang et al.'s (2009) connectionist model. First, the processing of Chinese characters is initiated by activating forms at the feature level, where sublexical orthographic units of characters are stored. At this stage, large combinability would induce increased activity at the feature level, and such a combinability effect would be revealed in the right fusiform gyrus at 170 ms. Then, feature units would activate their corresponding units, such as the representations of phonograms which are stored in the hidden layers. Yang et al. (2009) analyzed hidden units and indicated that characters sharing the same phonetic radical would form a tight cluster in the hidden layer. Therefore, we speculated that the second level of the connectionist model might exploit the combinability effect in the left anterior insula at 230 ms. That is, this model might predict that the interactive connections between hidden units would facilitate processing of word recognition, so processing large combinability characters would be faster than processing small combinability characters. Nevertheless, more studies are needed to evaluate how hidden units form representations of words (Chang, Furber, & Welbourne, 2012; Plaut, McClelland, Seidenberg, & Patterson, 1996).

Regarding the consistency effect in the activity of the left inferior parietal cortex at $\sim$200 ms, this finding supports a variety of fMRI and ERP/MEG studies demonstrating sublexical phonological processing. Previous brain imaging studies have indicated that the left inferior parietal cortex supports the integration of orthography and phonology in visual word recognition (Booth et al., 2002, 2003). For example, fMRI and PET studies of reading English words have demonstrated consistency and regularity effects in the left inferior parietal cortex (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Bolger et al., 2008; Fiez et al., 1999). Furthermore, fMRI studies of Chinese character recognition have also demonstrated consistency effects in the left inferior parietal cortex (Lee et al., 2010, 2004). This cross-linguistic evidence indicates that reading low consistency words generally yields greater activity in the left inferior parietal cortex than reading high consistency words. Previous ERP studies across different writing systems have also demonstrated that the amplitude of P200 is sensitive to regularity effects in reading English words (Sereno, Rayner, & Posner, 1998) and to phonetic consistency effects in reading Chinese phonograms (Hsu et al., 2009; Lee et al., 2007). One MEG study also suggested that the M250 activity, which seems to be the MEG counterpart of P200 activity, showed an effect of phonotactic probability in visual word recognition (Pylkkänen, Stringfellow, & Marantz, 2002). Taken together, the findings of previous studies and our results suggest that early activities in the left inferior parietal cortex are associated with processing of orthography-to-phonology conversion.

5. Conclusion

This study was designed to evaluate the neural correlates supporting the early EEG/MEG components of neighborhood effects. The results indicated significant effects of phonetic combinability and consistency in the activities of the left anterior insular cortex and the left inferior parietal cortex, respectively, at 250 ms. These findings support the assumption based on MROM and ERP studies that early ERP/MEG markers might index the sublexical processing underlying visual word recognition. Processing of the orthography-to-phonology conversion accounts for the increased activation in the left inferior parietal cortex in response to low consistency characters. Additionally, the facilitated processing seen when reading large combinability characters reflects a reduced activation of the left anterior insular cortex.

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Appendix A. Target characters

High consistency large combinability			
僕	/pu2/ servant	踰	/yu2/ to cross
鐐	/liao2/ shackles	猙	/zheng1/ ferocious
燐	/lin2/ phosphorous	鋸	/ju4/ a saw
朧	/long2/ blurred	脛	/jing4/ the shin
瀘	/lu2/ name of a river in China	鋰	/li3/ lithium
饑	/ji1/ hungry	蛾	/e2/ a moth
瑾	/jin3/ jade	姪	/zhi2/ nephews/nieces
漣	/lian2/ ripples	誅	/zhu1/ to condemn
嫖	/piao2/ to wench	絞	/jiao3/ to twist
嗷	/ao2/ crying	砥	/di3/ a whetstone
饅	/man2/ steamed buns	炬	/ju4/ a torch
愕	/e4/ astounded	羚	/ling2/ an antelope
煒	/wei3/ bright	蛀	/zhu4/ to bore through
醐	/hu2/ clarified butter	肪	/fang2/ fat
徨	/huang2/ agitated	伕	/fu1/ a groom
High consistency small combinability			
殤	/shang1/ to die in childhood	鱔	/shan4/ a moray eel
瑣	/suo3/ trifles	嬉	/xi1/ to play
瑙	/nao3/ agate	鎚	/chui2/ to hammer
愜	/qie4/ to be satisfied	碾	/nian3/ to crush with a roller
珮	/pei4/ jade	稼	/jia4/ to plant
纓	/ying1/ ribbon	醣	/tang2/ a carbohydrate
曦	/xi1/ sunlight	瞑	/ming2/ to close eyes
瀝	/li4/ to drip	腺	/xian4/ a gland
檬	/meng2/ a lemon	腱	/jian4/ a tendon
燼	/jin4/ cinders	啄	/zhuo2/ to peck
鐳	/lei2/ radium	婕	/jie2/ goodly
膿	/nong2/ pus	胰	/yi2/ the pancreas
曙	/shu4/ dawn	酩	/ming2/ drunk
璦	/ai4/ fine jade	鈽	/bu4/ plutonium
墟	/xu1/ ruins	仟	/qian1/ thousand
Low consistency large combinability			
鑲	/xiang1/ to inlay	誦	/song4/ to recite
臍	/qi2/ the navel	悚	/song3/ terrified
殮	/lian4/ to coffin	皓	/hao4/ white
贍	/shan4/ to provide for	齦	/yin2/ gums
橙	/cheng2/ an orange	珪	/gui1/ a jade tablet
蟠	/pan2/ to coil	柚	/you4/ a pomelo
縷	/lu3/ a thread	貽	/yi2/ to bequeath
嶇	/qu1/ rugged	貂	/diao1/ a marten
嫂	/sao3/ a sister in law	骷	/ku1/ a skeleton
倩	/qian4/ elegant	拈	/nian3/ to pick up
踝	/huai2/ an ankle	絆	/ban4/ to trip
醋	/cu4/ vinegar	蚱	/zha4/ a locust
惆	/chou2/ disconsolate	詛	/zu3/ to curse
猝	/cu4/ sudden	岐	/qi2/ divergent
賑	/zhen4/ to relieve	奸	/jian1/ crafty
Low consistency small combinability			
綴	/zhui4/ to stitch	踱	/duo4/ to pace
躡	/nie4/ to walk softly	琥	/hu3/ amber
殲	/jian1/ to destroy	綻	/zhan4/ to burst
獺	/ta4/ an otter	陡	/dou3/ steep
璿	/xuan2/ fine jade	琇	/xiu4/ jade
韃	/da2/ Tartars	恬	/tian2/ tranquil
橘	/ju2/ a tangerine	佰	/bai3/ a hundred
僭	/jian4/ to overstep	詣	/yi4/ attainment
鏽	/xiu4/ rust	絨	/rong2/ velvet
橄	/gan3/ an olive	缽	/bo1/ a bowl
蹲	/dun1/ to squat	歿	/mo4/ death
瞠	/cheng1/ to stare	舐	/shi4/ to lick
鰭	/qi2/ a fin	靴	/xue1/ boots
瞎	/xia1/ to be blind	酗	/xu4/ drunk
喙	/hui4/ a beak	叭	/ba1/ a trumpet

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