


RESEARCH ARTICLE

Neural representation of phonological information during Chinese character reading

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Abstract

Previous studies have revealed that phonological processing of Chinese characters elicited activation in the left prefrontal cortex, bilateral parietal cortex, and occipitotemporal regions. However, it is controversial what role the left middle frontal gyrus plays in Chinese character reading, and whether the core regions (e.g., the left superior temporal gyrus and supramarginal gyrus) for phonological processing of alphabetic languages are also involved in Chinese character reading. To address these questions, the present study used both univariate and multivariate analysis (i.e., representational similarity analysis, RSA) to explore neural representations of phonological information during Chinese character reading. Participants were scanned while performing a reading aloud task. Univariate activation analysis revealed a widely distributed network for word reading, including the bilateral inferior frontal gyrus, middle frontal gyrus, lateral temporal cortex, and occipitotemporal cortex. More importantly, RSA showed that the left prefrontal (i.e., the left middle frontal gyrus and left inferior frontal gyrus) and bilateral occipitotemporal areas (i.e., the left inferior and middle temporal gyrus and bilateral fusiform gyrus) represented phonological information of Chinese characters. These results confirmed the importance of the left middle frontal gyrus and regions in ventral pathway in representing phonological information of Chinese characters.

KEYWORDS

Chinese character, fMRI, phonological processing, reading, representational similarity analysis

1 | INTRODUCTION

Phonological processing (i.e., transforming the visual forms of written words into sounds) is one of key components of reading (Coltheart et al., 2001; Harm & Seidenberg, 2004). Numerous neuroimaging studies have examined the neural basis of phonological processing in reading by using various reading tasks, such as rhyme judgment (Aparicio et al., 2007; Booth et al., 2004; Dębska et al., 2019; Kim

et al., 2020; Liu et al., 2009, 2018; Mathur et al., 2020; Pillay et al., 2014; Tan et al., 2003; Yen et al., 2019), homophone judgment (Chuchu et al., 2018; Gitelman et al., 2005; Matsuo et al., 2010; Siok et al., 2003; Tham et al., 2005; Yang & Tan, 2019), initial consonant judgment (Lee et al., 2012; Siok et al., 2003), phonological decision (Emmorey et al., 2016; Hartwigsen et al., 2010; Liebig et al., 2017), silent reading (Cheema et al., 2018; Cullum et al., 2019; Hartwigsen et al., 2010; Kumar & Padakannaya, 2019; Lu et al., 2021; Osipowicz

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et al., 2011; Qu et al., 2019; Wan et al., 2017), and overt naming tasks (Al et al., 2020; Berken et al., 2015; Binder et al., 2005; Brumberg et al., 2016; Dietz et al., 2005; Dong et al., 2020, 2021; Graves et al., 2010; Mechelli et al., 2007). Researchers have observed consistent activation in language-related brain areas in the left inferior frontal gyrus, left temporoparietal cortex, and left lateral temporal cortex. Among those regions, the left dorsal brain circuit including the temporoparietal cortex and dorsal inferior frontal gyrus is widely considered to be core regions for phonological processing of alphabetic words (Hickok, 2012; Zuk et al., 2018; Oron et al., 2016; Vigneau et al., 2006). The left temporoparietal cortex (i.e., the posterior superior temporal gyrus and supramarginal gyrus) is thought to be responsible for grapheme-to-phoneme conversion in alphabetic word reading (Glezer et al., 2016; Price, 2012; Pugh et al., 2001). In contrast, the left ventral inferior frontal gyrus and the inferior and middle temporal gyrus are thought to be related to semantic processing during word reading (Binder et al., 2009; Booth et al., 2006; Gesa et al., 2016; Jana & Gesa, 2019; Katzev et al., 2013; Miozzo et al., 2017; Price, 2000; Pugh et al., 2005).

The above neural network for phonological access is mainly identified based on research on alphabetic languages (e.g., English and French). Chinese characters, as a logographic script, differ notably from alphabetic words in several aspects such as visual appearance and orthography (Chen et al., 2009). For example, Chinese characters consist of intricate strokes that are packed into a square configuration, whereas alphabetic words are linear combination of letters. In terms of phonological access (i.e., mapping orthography onto phonology), Chinese character's phonology is defined at the syllabic level with no parts in the character corresponding to phonological segments such as phonemes (Perfetti & Tan, 1998). In contrast, alphabetic word's phonology is defined at the phonemic level, and reading alphabetic words makes more use of grapheme-to-phoneme conversion (Perfetti et al., 2005; Tan & Perfetti, 1998). Those discrepancies in linguistic features imply that Chinese characters and alphabetic words may differ in neural mechanisms of phonological processing.

A number of functional neuroimaging studies have implicated the particularity of neural patterns for phonological processing in Chinese character reading. For instance, the left middle frontal gyrus (MFG) at Brodmann area (BA) 9, a region that is rarely reported in neuroimaging studies of alphabetic words, activates during phonological processing of Chinese characters (Booth et al., 2006; Cao et al., 2009, 2011, 2013; Cao & Perfetti, 2016; Kuo et al., 2004; Nelson et al., 2009; Tan et al., 2001, 2003; Xu et al., 2015). Further evidence suggests that functional and structural abnormality in the left MFG is associated with Chinese dyslexia (Siok et al., 2004, 2008, 2009). In contrast, the left posterior superior temporal gyrus and adjacent supramarginal gyrus, the critical regions for phonological processing of alphabetic words (Bolger et al., 2005; Brennan et al., 2013; Oberhuber et al., 2016), are not involved in Chinese reading (Cao et al., 2009; Tan et al., 2003). Those findings have been confirmed by meta-analyses on the neural mechanisms of Chinese character reading (Bolger et al., 2005; Tan et al., 2005; Wu et al., 2012; Zhu et al., 2014). For example, Tan et al. (2005) analyzed six functional imaging studies, and

identified four key neural systems responsible for Chinese character reading: (1) a left dorsal lateral frontal system (BA9); (2) the dorsal aspect of left inferior parietal system; (3) a bilateral ventral occipitotemporal system; and (4) a left ventral prefrontal system covering superior portions of inferior frontal gyrus.

Although much is known about the neural activation patterns for phonological processing of Chinese characters, it is still controversial whether the left MFG and temporoparietal cortex are involved in the phonological processing of Chinese characters and what function those regions carry. First, although many studies have shown that the left MFG is engaged during Chinese reading (Booth et al., 2006; Cao et al., 2009, 2011, 2013; Cao & Perfetti, 2016; Kuo et al., 2004; Nelson et al., 2009; Tan et al., 2001, 2003; Xu et al., 2015), lack of activation in the left MFG has been reported in a number of other studies on Chinese character reading (Wang et al., 2019; Xue et al., 2004, 2005; Yu et al., 2018). Several researchers believe that the left MFG is responsible for addressed phonology (Tan et al., 2005) or visuospatial analysis (Cao et al., 2011; Chen et al., 2016; Liu et al., 2009) in Chinese character reading, while others think that it is related to cognitive control (Courtney et al., 1998; Eayrs & Lavie, 2019; Hernandez et al., 2001; Wang et al., 2007) or working memory (Feng et al., 2020; Ip et al., 2017; Ziegler, 2006) during phonological processing of Chinese characters. Therefore, whether the left MFG is involved in Chinese character reading and what role it plays in Chinese character reading should be further elaborated on. Second, it is unclear whether the left temporoparietal cortex, the core area for phonological processing of alphabetic words (Bolger et al., 2005; Brennan et al., 2013; Oberhuber et al., 2016; Tan et al., 2005), is also critical for Chinese reading. Many studies have reported that the left posterior superior temporal gyrus and adjacent supramarginal gyrus are not involved in the phonological task on Chinese characters (e.g., Cao et al., 2009; Siok et al., 2003; Tan et al., 2003). Lack of activation in those two regions in Chinese reading has been interpreted as the particularity of Chinese phonological processing, as there is no grapheme-phoneme correspondence in Chinese characters. In support of this view, meta-analysis studies have revealed that the left posterior superior temporal gyrus is more engaged in alphabetic languages than in logographic ones (Bolger et al., 2005; Tan et al., 2005). Nevertheless, there is also evidence for increased activation in the left posterior superior temporal cortex in Chinese character reading with the increasing demands on phonological processing (Hu et al., 2010). Besides, one recent study has asked children from alphabetic (i.e., French) and nonalphabetic (i.e., Chinese) languages to perform passive viewing task with words, faces, and houses (Feng et al., 2020). Results showed that, compared with French children, Chinese children showed greater activity in the left intraparietal sulcus and left posterior superior temporal sulcus under the words versus fixation contrast. The researchers have speculated that despite Chinese readers rely heavily on the direct route from orthography to the lexicon, phoneme-level representation still plays an essential role in learning to read Chinese characters. Therefore, the left temporoparietal regions (i.e., the left posterior superior temporal gyrus and left supramarginal gyrus) should be included to investigate neural representations of Chinese phonological processing.

The above inconsistent results could be accounted by at least three reasons. First, the definition of the left MFG varies across studies. Specifically, most studies defined the left MFG as region of interest (ROI) based on previous literature. Because of the subjectivity on the selection of references, the location of the defined ROI varies from the left MFG (Cao & Perfetti, 2016; Ip et al., 2017; Liu et al., 2009) to inferior frontal gyrus (IFG; Cao & Perfetti, 2016; Zhang et al., 2004). In addition to the location differences, the size of the defined left MFG also differs across studies. The radius of the defined region varies from 6 to 10 mm (Cao & Perfetti, 2016; Ip et al., 2017; Siok et al., 2008). The inconsistent results on the left MFG might be caused by its location and size differences across different studies. Therefore, the present study defined the left MFG based on literature, brain structure, and a localizer task to comprehensively examine the role of the left MFG in Chinese character processing. Second, the inconsistent results might be attributed to task differences. Specifically, studies using implicit reading tasks (e.g., passive viewing task and lexical decision task; Wang et al., 2019; Xue et al., 2005; Yu et al., 2018), failed to observe activation in the left MFG during Chinese characters reading. In contrast, the left MFG is found to be involved in the phonological processing of Chinese characters when explicit reading tasks (e.g., reading aloud task) were used (Kuo et al., 2003; Lee et al., 2004). Compared with implicit reading tasks, explicit reading tasks require higher demand for phonological processing, and consequently are more likely to elicit the activation of brain regions related to phonological processing. As mentioned before, there is evidence for increased activation in the left posterior superior temporal cortex in Chinese character reading with the increasing demand for phonological processing (Hu et al., 2010). Therefore, the explicit reading tasks (e.g., reading aloud task) with relatively high demand for phonological processing are needed for the investigation of phonological processing of Chinese characters. Finally, previous studies mainly used traditional univariate activation analysis, which is not able to investigate the nature of representations in brain regions activating in the phonological tasks. In other words, it is unclear whether activation in a particular brain region reflects phonological processing per se or other cognitive processes (e.g., cognitive control). Therefore, multivariate approaches (e.g., representational similarity analysis, RSA) should be used to specify information representations in the left MFG and temporoparietal regions. By quantitatively correlating the brain-activity measurement with behavioral measurements, RSA is able to detect the information carried by a given neural pattern in a brain region (Kriegeskorte et al., 2008).

To overcome the above limitations, the current study (1) defined the regions of interest (ROIs) based on a localizer task (i.e., rhyme judgment task), Harvard-Oxford atlas, and literature; (2) adopted an explicit reading task (i.e., reading aloud task) with relatively high demand of phonological processing; and (3) conducted RSA to explore the neural representations of phonological information during Chinese character reading. Specifically, 27 native Chinese speakers were recruited to perform two Chinese phonological tasks (i.e., the rhyme judgment task and reading aloud task). We first localized brain areas

involved in phonological processing by using the rhyme judgment task in which participants had to judge whether each pair of Chinese characters rhymed. We additionally defined the left posterior superior temporal gyrus, anterior supramarginal gyrus, and MFG based on Harvard-Oxford atlas and the left MFG based on literature (Tan et al., 2005) as ROIs. To explore whether those regions represented phonological information of Chinese characters, RSA was then performed on the data of the reading aloud task by correlating neural dissimilarity matrices with phonological dissimilarity matrices of the Chinese characters used in the reading aloud task. A given region would represent phonological information if its correlation was significant.

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-eight native Chinese speakers participated in the study. One participant was removed from data analysis due to excessive head movement during scanning, resulting in 27 participants (13 males, mean age = 20.15, SD = 1.69, range = 18–25) for subsequent analysis. The number of subjects was sufficient for investigating the phonological representation in Chinese character reading according to the following analysis. Following the methods in Westfall et al. (2014), 27 participants and 34 stimuli (see below) per condition could reach a good starting point for effect sizes of $d = 0.5$. A power analysis (implemented in G*Power) on this effect size revealed that a sample size of 27 would give power of 0.812.

All participants were strongly right-handed (mean = 78.40, SD = 15.20) as assessed by Snyder and Harris's handedness inventory (Snyder & Harris, 1993). Participants' reading speed was assessed using Chinese word efficiency test (104 items) designed by the authors in this study before fMRI scanning. It was scored by the number of correctly named items within 40 s. The mean score was 90.26 (SD = 7.19), indicating that participants were proficient in reading Chinese characters. All participants had normal or corrected-to-normal vision. None of them had a history of head trauma and neurological or psychiatric disease. They gave written informed consent before the experiment. The study was approved by the IRB of the School of Psychology at South China Normal University.

2.2 | Materials

Materials contained 106 Chinese characters and 2 grate images with different orientations. They were presented in gray scale with 302×302 pixels in size. Thirty-six pairs of Chinese characters (i.e., 72 characters) were used for the localizer task (i.e., rhyme judgment) and the rest (i.e., 34 Chinese characters) were used for the reading aloud task. The characters were presented in black color against a grey background. The grate images were tilted to the left or the right of the vertical axis (tilting 45°).

For the localizer task, 36 pairs of Chinese characters were selected from a Chinese database (Cai & Brysbaert, 2010). Half pairs rhymed and the other half did not (see Table S1). They consisted of 2–8 strokes (mean = 5.72, SD = 1.61), and were medium- to high-frequency (mean = 106.32 per million, SD = 142.29). To ensure that they were familiar to participants, we recruited another 15 Chinese participants to evaluate the familiarity of the Chinese characters on a 7-point scale (1 = “very unfamiliar”, 7 = “very familiar”). The mean score was 6.57 (SD = 0.29), suggesting these Chinese characters were highly familiar to participants. The number of strokes were identical, and there was no significant difference in frequency ($t(35) = 0.443$, $p = .660$) and familiarity ($t(35) = -0.225$, $p = .823$) between the two pairs of Chinese characters. There were eight polyphone characters in the materials of localizer task. We picked out “Wcount” of words containing the eight characters from a Chinese database (Cai & Brysbaert, 2010), and calculated the percentage pronounced as the dominant pronunciation for each of the eight polyphone characters. The probabilities of the dominant pronunciation ranged from 0.721 to 0.999 (mean = 0.903, SD = 0.135). In addition, all the eight polyphone characters had multiple pronunciations with the same rime. Therefore, participants' responses in the rhyme judgment task would not be affected by polyphones in the present study.

For the reading aloud task, 34 Chinese characters were chosen from a previous study (Zhao et al., 2017, see Table S2). They consisted of 4–17 strokes (mean = 8.62, SD = 3.02), and their mean frequency was 20.12 per million (SD = 56.60). All materials had left-right configuration with the phonetic radicals situated in the right half of the character to eliminate the confounding effects of phonetic radical position (Liu et al., 2020, 2022). The characters formed 561 pairs ($34 \times [34-1]/2 = 561$) in the following four categories in terms of orthographic and phonological similarities: (1) 28 pairs that were similar in orthography and phonology; (2) 33 pairs that were similar in orthography but different in phonology; (3) 52 pairs that were different in orthography but similar in phonology; and (4) 448 pairs that were different in orthography and phonology. Therefore, the orthographic dissimilarity matrix (DSM) and the phonological DSM of those 34 Chinese characters were minimally correlated based on subjective ratings (see below), which was conducive to separate the representations of orthographic and phonological information.

2.3 | fMRI task

The fMRI scan included two runs of the localizer task and four runs of the reading aloud task. The localizer task aimed to localize brain areas involved in the phonological processing of Chinese characters. In the localizer task, participants were asked to decide whether a pair of Chinese characters rhymed with each other. The reading aloud task was used to explore which regions represented the phonological information of Chinese characters. In the reading aloud task, participants were asked to overtly name characters to ensure phonology was explicitly accessed. Before the fMRI scan, participants were given a brief practice session to be familiarized with the procedure. Characters used in the practice session were not presented during the fMRI scan.

In the localizer task, each run lasted for 376 s. A block design was used for the localizer task (Figure 1a). Each run consisted of nine blocks, with three blocks for rhyme judgment of Chinese characters, three blocks for rhyme judgment of English words, and three blocks for orientation judgment. English materials were included to address other research questions, and thus excluded from data analysis in this article. The task blocks were interleaved with 16 s baseline (i.e., fixation) blocks. The blocks were arranged in Latin square order. There were six trials in each block. Each trial started with a 500 ms fixation, followed by two stimuli (Chinese characters, English words, or grate images) presented sequentially. The first stimulus was presented for 500 ms, followed by a 500 ms blank interval. The second stimulus was presented for up to 2500 ms and disappeared once a response was made. Thus, each trial lasted for 4000 ms. Participants were instructed to judge whether the second character or word rhymed with the first one in the rhyme judgment task or whether the orientation of the second grate was identical to that of the first one by pressing one of the two buttons.

In the reading aloud task, each run consisted of 34 trials and lasted for 408 s. Following previous studies (e.g., Fischer-Baum et al., 2017; Taylor et al., 2019; Zhao et al., 2017), the present study repeated the 34 characters for four times to increase design efficiency (Kriegeskorte et al., 2008) and signal-to-noise ratios (A. Cheveigné, 2014; Cheveigné et al., 2018). Each character was presented only once within a run to reduce the repetition priming effects, and the four pseudorandom stimulus sequences were different to minimize order effects. A slow event-related design (12 s per trial) was used to precisely estimate the BOLD signal associated with a single trial (Figure 1b). Each trial started with a 1000 ms fixation, followed by a Chinese character presented in the center of the

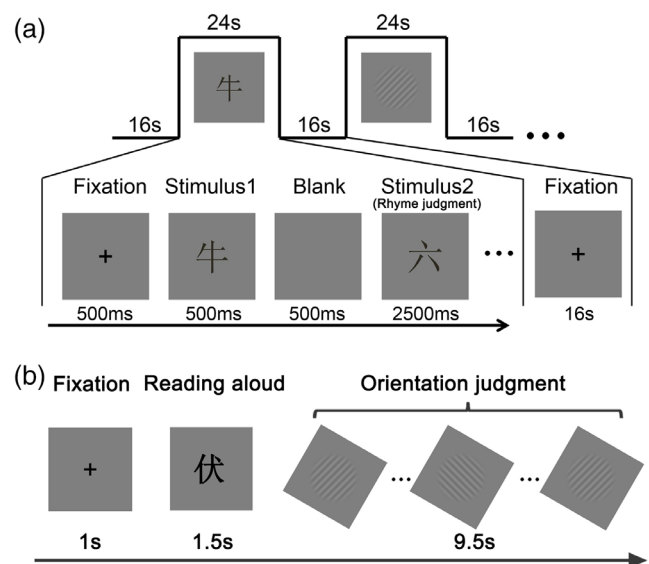


FIGURE 1 Experimental designs of fMRI tasks. (a) In the localizer task, participants had to judge whether the second character/grate matched with the first one. (b) In the reading aloud task, participants were instructed to overtly read each character as quickly and accurately as possible.

screen for 1500 ms. Participants were instructed to overtly name each character as quickly and accurately as possible while keeping their heads still. To prevent participants from further rehearsing the characters, they were asked to complete a self-paced visual orientation judgment task for 9500 ms (Xue et al., 2013; Zhao et al., 2017), where participants had to judge whether the grate image tilted to the left (by pressing the button “1”) or the right (by pressing the button “4”) of the vertical axis. Once participants responded, the current image disappeared and the next grate image appeared after a 100 ms blank. The mean accuracy was 0.869 (SD = 0.019) in the orientation judgment task, suggesting participants were concentrating on the task. Due to the large amount of noise during scanning, the behavioral responses of the reading aloud task (i.e., accuracy and reaction time) were recorded after scanning. The trial sequences and experimental parameters were the same as the fMRI reading aloud task.

2.4 | Rating- and model-based dissimilarity matrices

After the fMRI scan, participants were asked to rate orthographic, phonological, and semantic similarities on a 7-point scale (1 = “completely different”, 7 = “identical”) for every possible pair of the 34 characters ($34 \times [34-1]/2 = 561$ pairs) used in the reading aloud task. Several critical features were instructed to be considered during subjective rating. Specifically, for the orthographic similarity, participants had to evaluate the amount of overlap in terms of the radicals, number of strokes, and spatial organization (left–right or top–down) of the characters. For the phonological similarity, participants were instructed to evaluate how similar the characters were to each other in terms of the onset (or “shengmu”, which contains only the initial consonant), rime (or “yunmu”, which includes any semivowels, nuclear vowels, and codas), and the tones of Chinese characters. For the semantic similarity, participants evaluated how similar the characters were to each other in terms of the meaning. To ensure that participants understood the meanings of orthographic, phonological, and semantic similarities, we provided examples of character pairs that were “identical” and “completely different” for the rating tasks. The rating scores were reversed (i.e., 8 minus the rating score) in data analysis to generate an intuitive index of dissimilarity, with 1 = “identical” and 7 = “completely different.” The reversed ratings from the 27 participants were averaged, resulting in 34×34 matrices of orthographic dissimilarities (Table S5), phonological dissimilarities (Table S3), and semantic dissimilarities (Table S6). Spearman’s rank correlation analysis showed that the orthographic dissimilarity and phonological dissimilarity were minimally correlated ($r = .091$, $p = .032$). Multiple dimensional scaling revealed a good dispersion for orthography (Figure 2a) and phonology (Figure 2b) of the 34 Chinese characters.

Beside the behavioral ratings, a computational model built by Yang et al. (2009) was used to evaluate the phonological dissimilarity for every possible pair of the 34 characters. This model reflected important features of Mandarin syllables based on a phonetic

description of Standard Mandarin (Huang & Liao, 2002). In this model, the phonological representation of each character composed of five slots (see Figure S2), with 1 for the onset (i.e., initial consonant), 3 for the rime (i.e., semivowels, nuclear vowels and codas), and the fifth slot composed of 4 units to represent lexical tone. For the four slots representing phonemes, each consisted of three subgroups: (1) 8 units encoded manner (e.g., stop, affricate, fricative, semivowel/liquid, vowel); (2) 6 units encoded place (e.g., dental, retroflex, palatal, velar); and (3) 8 units encoded impressionistic vowel quality, with 1 unit to code retroflexing, 2 to represent backness, 3 for height, and 2 for lip rounding. Thus, the phonology of each character was coded as a binary vector of 92 binary units. The phonological dissimilarities were calculated by 1 minus cosine similarity for all possible pairs of those vectors (561 pairs in total). All the dissimilarity values were transformed into Fisher’s Z-scores, resulting in a 34×34 model-based phonological dissimilarity matrix (Table S4). Spearman’s rank correlation analysis showed that rating- and model-based phonological dissimilarities were highly correlated ($r = .857$, $p < .001$).

2.5 | MRI data acquisition

All MRI images were collected using a 3.0 T Siemens MRI scanner in the MRI Center at South China Normal University. Functional images were acquired with a single-shot T2*-weighted gradient-echo EPI sequence (32 axial slices, TR/TE/θ = 2000 ms/30 ms/90°, FOV = 224 × 224 mm, matrix size = 64 × 64, slice thickness = 3.5 mm). Anatomical images were acquired with a T1-weighted, three-dimensional, gradient-echo pulse-sequence (176 sagittal slices, TR/TE/θ = 1900 ms/2.52 ms/9°, FOV = 256 × 256 mm, matrix size = 256 × 256, slice thickness = 1 mm).

2.6 | Activation analysis

Image processing was performed using FEAT Version 6.00 in FSL (FMRIB’s Software Library, <http://www.fmrib.ox.ac.uk/fsl>). The first three volumes in each time series were discarded to remove non-equilibrium effects of T1. The remaining images were then realigned. Data of one participant were removed from the subsequent analysis due to excessive head movement during scanning. For the remaining participants, no translational movement parameters exceeded 1 voxel in any direction for any run. The functional data were spatially smoothed using a Gaussian kernel of 5 mm full-width-half-maximum (FWHM) and then temporally filtered by using a nonlinear high-pass filter with a 60-s cutoff. The functional images were registered to standard Montreal Neurological Institute (MNI) space using a two-step registration from functional to the MPRAGE structural image to MNI-template (Jenkinson & Smith, 2001).

Three levels of analyses were carried out. At the first level of analysis, the data were modeled with the general linear model for each participant and each run. The onsets (the onset of each block in the localizer task, and the onset of each character in the reading aloud

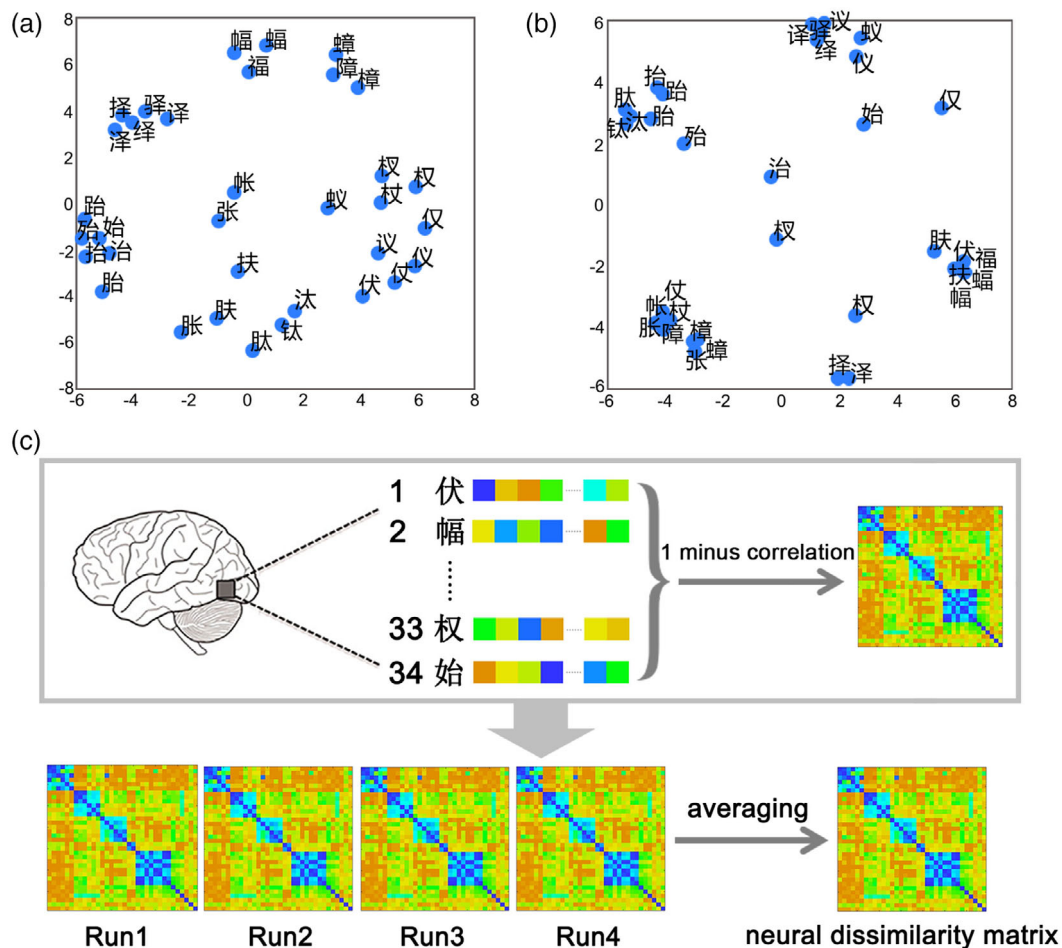


FIGURE 2 Dissimilarity space of the 34 Chinese characters as revealed by multiple dimensional scaling and the calculation of neural pattern dissimilarity. (a) Orthographic dissimilarity structure for the 34 Chinese characters based on subjective ratings. (b) Phonological dissimilarity structure based on subjective ratings. Each dot represents a Chinese character with its label by its side, and the distance between a pair of dots represents the dissimilarity of them. The farther away two dots are, the more dissimilar they are to each other. (c) Calculation of neural pattern dissimilarity. Activation patterns were extracted for each of the 34 characters in each run. Then all possible pairs of these 34 activation patterns were subjected to Pearson correlation analysis, and the neural dissimilarity was computed by 1 minus the Pearson correlation, resulting in a 34×34 matrix of the neural dissimilarity in each run. All of the dissimilarity coefficients were averaged across the 4 runs to obtain the mean neural dissimilarity matrix.

task) and durations (24 s in the localizer task, and 1.5 s in the reading aloud task) of the events were convolved with double-gamma hemodynamic response function to generate the regressors used in the general linear model. The fixation and orientation judgment tasks were not explicitly modeled, and consequently served as implicit baseline. The contrast of rhyme judgment minus orientation judgment was calculated for each participant and each run. Images for reading aloud task were modeled for each participant and each run. To improve statistical sensitivity, the six motion parameters and temporal derivatives were included as covariates of no interest.

Then the second-level analysis was performed for each participant to concatenate the imaging data across two runs of localizer task and across four runs of reading aloud task by using a fixed-effects model. Finally, group-level analysis was carried out using FLAME (FSL's local analysis of mixed-effects) Stage 1 only (i.e., without the final Markov-Chain-Monte-Carlo-based stage; Beckmann et al., 2003;

Woolrich et al., 2004). All reported group images were thresholded with a height threshold of $Z > 2.6$ (i.e., $p < .005$) and a cluster probability of $p < .05$, corrected for whole-brain multiple comparisons using the Gaussian random field theory (Worsley, 2001).

2.7 | Region of interest analysis

A total of 11 regions of interest (ROIs) were defined in the present study (Figure 5a). First, we used the contrast of rhyme judgment > orientation judgment ($Z > 2.6$, whole-brain corrected) in the localizer task to identify brain areas involved in phonological processing of Chinese characters. In this analysis, six regions including the left middle frontal gyrus (MFG), left inferior frontal gyrus (IFG), bilateral fusiform gyrus (FFG), left inferior temporal gyrus (ITG), and left middle temporal gyrus (MTG) were identified as ROIs (Figure 4b and Table 1). Because the localizer task included

TABLE 1 Regions of interest (ROIs) defined based on the localizer task ($Z > 2.6$, corrected), Harvard–Oxford atlas, and literature (Tan et al., 2005)

Regions	x		y		z		Z	Voxels
	Min	Max	Min	Max	Min	Max		
<i>Rhyme > Orientation judgment</i>								
Left middle frontal gyrus	−54	−34	6	22	18	40	4.17	108
Left inferior frontal gyrus	−62	−36	8	34	−6	30	4.90	1162
Left inferior temporal gyrus	−56	−46	−64	−14	−38	−6	5.99	501
Left middle temporal gyrus	−70	−54	−54	−12	−8	2	4.16	149
Left fusiform gyrus	−48	−26	−72	0	−42	−4	6.03	2132
Right fusiform gyrus	30	48	−66	0	−44	−14	5.34	947
<i>Harvard–Oxford atlas</i>								
Left middle frontal gyrus	−54	−24	−6	36	17	66	4.17	2755
Left posterior superior temporal gyrus	−70	−47	−42	−9	−12	18	2.93	877
Left anterior supramarginal gyrus	−68	−35	−40	−21	19	54	1.99	946
<i>Literature</i>								
Left middle frontal gyrus	−54	−37	13	30	19	36	4.51	389
Left inferior parietal lobule	−44	−27	−48	−31	41	58	1.81	389

blocks of both Chinese characters and English words, it is possible that the definition of those ROIs might have been affected by language switching. To eliminate such confounding effects, we re-calculated the contrast of rhyme judgment > orientation judgment by including four blocks of Chinese characters without language switching, and found that activations were almost the same as before (see Figure S3).

Second, the left posterior superior temporal gyrus (STG) and left anterior supramarginal gyrus (SMG) were anatomically defined as two ROIs based on Harvard–Oxford atlas (Maximal Probability Threshold: 25%) within FSL because of their crucial involvement in phonological processing of alphabetic words (Bolger et al., 2005; Brennan et al., 2013; Oberhuber et al., 2016; Tan et al., 2005).

Third, to specifically examine whether the left middle frontal gyrus represented the phonological information of Chinese character, we additionally defined the left MFG (1) based on Harvard–Oxford atlas (Maximal Probability Threshold: 25%) within FSL, and (2) as a sphere of 9 mm radius around the coordinate (MNI: −46, 23, 24) at Brodmann Area 9 reported in Tan et al. (2005).

Finally, the left inferior parietal lobule (IPL), which was thought to contain short-term storage of phonological codes (Tan et al., 2005), was defined as a sphere of 9 mm radius around the coordinate (MNI: −36, −42, 48) at Brodmann Area 40 reported in Tan et al. (2005). It should be noted that this region is located more superior to the left SMG and close to the superior parietal lobule (SPL). Those 11 ROIs were defined for the subsequent representational similarity analysis.

2.8 | Representational similarity analysis

To examine the neural representation of phonological information during Chinese character reading, we performed both ROI-based

representational similarity analysis (RSA) and whole-brain RSA by correlating neural dissimilarity matrices with the phonological dissimilarity matrices of the 34 Chinese characters used in the reading aloud task. The same preprocessing procedure as in the activation analysis was used except that no spatial smoothing was applied.

We first reran the first-level models of the reading aloud task by using unsmoothed data. The onsets, durations, and baseline were the same as those in activation analysis. Each character was modeled as one predictor. Thus, there were 34 predictors per run. Following previous studies (Dong et al., 2021; Mumford et al., 2012; Xiao et al., 2017; Xue et al., 2010), the model parameters were estimated using least squares estimation and ridge regression. The least squares estimate for the model parameters is calculated using the equation $\hat{\beta}_{ls} = (X'X)^{-1}X'Y$, where X is the design matrix and Y is the vector of the BOLD response time series. A ridge regression analysis was performed to remedy the collinearity problem. Its estimate is calculated using the formula $\hat{\beta}_T = (X'X + kI_p)^{-1}X'Y$, where T is the number of time points in the data, k is the biasing parameter, and I_p is a square identity matrix with the same number of columns as X . When $k = 0$, the ridge regression equation is equivalent to least squares, and larger k value adds more bias to the estimate. The optimal k value is determined using the formula of $k_{opt} = ps_{ls}^2 / \hat{\beta}'_{ls} \hat{\beta}_{ls}$, where s_{ls}^2 is the estimate of the error variance from the least squares regression equation defined by $s_{ls}^2 = (Y - X\hat{\beta}_{ls})'(Y - X\hat{\beta}_{ls}) / (T - 1)$ (Gibbons, 1981; Hoerl & Kennard, 1970).

In the whole-brain RSA, a searchlight method was used to locate brain regions across the whole brain (Li et al., 2019; Xue et al., 2013). As shown in Figure 2c, we extracted the activation patterns from a cubic region (125 voxels) centered on the target voxel for each of the 34 characters for each run and for each participant. Then, all possible pairs of these 34 activation patterns (561 in total) were subjected to

Pearson correlation analysis. The neural dissimilarity was computed by 1 minus the Pearson correlation, resulting in a 34×34 matrix of the neural dissimilarity in each run. All of the dissimilarity coefficients were then transformed into Fisher's Z-scores and averaged across the four runs to obtain the mean neural dissimilarity matrix (DSM).

In the ROI-based RSA, the mean neural dissimilarity matrices were computed within each of the 11 ROIs. Then, we calculated Spearman's rank correlation between the neural DSMs and the rating-based phonological DSM, and transformed those correlation coefficients into Fisher's Z-scores. To further confirm the robustness of our results, we also calculated Spearman correlations between neural DSMs and the model-based phonological DSM. Nonparametric permutation tests were conducted to determine the significance level of the Spearman correlations to avoid inflated false positive rates in statistical inference (Eklund et al., 2016). Specifically, the correlation between the neural DSM of each ROI and phonological DSM was taken as the actual observation. We randomly shuffled the phonological DSM, and then computed the Spearman correlation between the phonological DSM and the neural DSM of each ROI to obtain a null correlation value in each permutation. All correlation values were transformed into Fisher's Z-scores. We repeated this procedure 10,000 times and compared the observed Z-value to the null distribution from 10,000 permutations. The significance of the observed Z-value was calculated using the following equation: $p_{\text{uncorrected}} = ([\text{the number of permuted Z-values} > \text{the observed Z-value}] + 1)/10,001$. Family-wise errors (FWE) for multiple comparisons were controlled using maximal statistic during the permutation test (Nichols & Holmes, 2002). Specifically, during each iteration, the maximum null Z-value among all ROIs was selected, resulting in 10,000 maximum null Z-values. This maximum null distribution was compared to the observed Z-value. The FWE-corrected significance of the observed Z-value was calculated using the following equation: $p_{\text{corrected}} = ([\text{the number of null max Z-values} > \text{the observed Z-value}] + 1)/10,001$.

3 | RESULTS

3.1 | Behavioral results

For the reading aloud task (Figure 3a), the accuracies of all participants were higher than 97% (mean = 0.998, SD = 0.008) and the mean reaction time was 932.7 ms (SD = 128.34). These results suggest that participants were familiar with the materials. For the localizer task, participants also performed well. Paired-sample *t* test was used to examine the differences in behavioral performance between the rhyme judgment task and orientation judgment task. As shown in Figure 3b, the accuracy was higher for rhyme judgment (mean = 0.983, SD = 0.031) than orientation judgment (mean = 0.957, SD = 0.054; $t(26) = 2.091, p < .05$). For the reaction time, there was no significant difference between rhyme judgment (mean = 820.01 ms, SD = 153.91) and orientation judgment (mean = 798.64 ms, SD = 136.83) ($t(26) = 1.017, n.s.$). These results suggest that participants performed well during the localizer task.

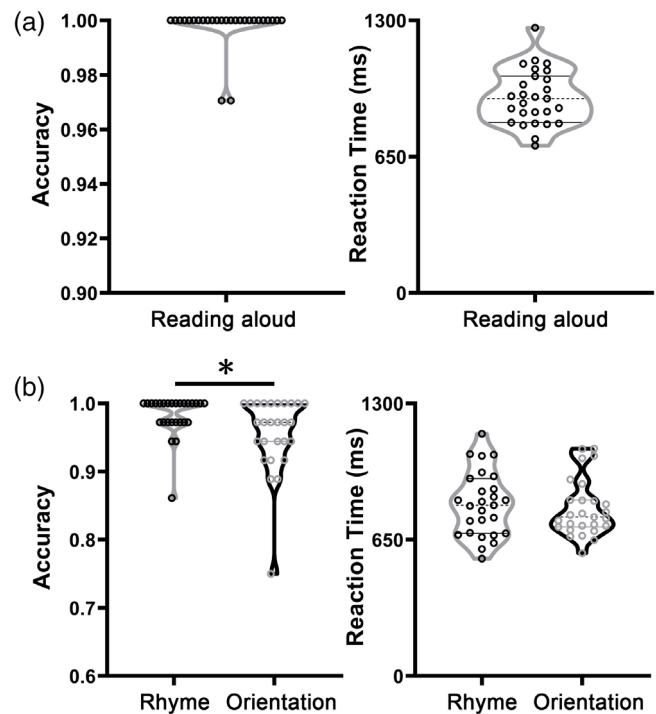


FIGURE 3 Behavioral performance for the reading aloud task (a) and the localizer task (b). Violin plots show the spread in accuracy and response time for reading aloud, rhyme judgment, and orientation judgment tasks. Behavioral responses of the reading aloud task were collected after scanning.

3.2 | Neural activations during the reading aloud task

For the reading aloud task, univariate activation analysis revealed a widely distributed network largely overlapping with the reading network found in the existing studies (Dong et al., 2020; Jobard et al., 2003; Tan et al., 2005; Zhao et al., 2017; Zhou et al., 2018). Specifically, reading Chinese characters elicited activation in brain regions included the bilateral precentral gyrus, inferior/middle frontal gyrus, lateral temporal cortex, and occipitotemporal cortex (Figure 4a and Table 2).

3.3 | Neural representations of phonological information in selected brain regions for reading

To examine which brain regions represented the phonological information of Chinese characters, we performed RSA on the reading aloud task within the 11 predefined ROIs for phonological processing (see Figure 5, Table 3, and Figure S4). First, for the six ROIs defined in the localizer task (i.e., the left middle frontal gyrus, inferior frontal gyrus, inferior temporal gyrus, middle temporal gyrus, and bilateral fusiform gyrus), all correlation coefficients were significant (all $ps < .01$) between neural DSMs and the rating-based phonological DSM. Those correlation coefficients were still significant after

FIGURE 4 Brain activations for Chinese characters during the reading aloud task (a) and the localizer task (b). All the activations were thresholded at $Z > 2.6$ (whole-brain corrected). R, right.

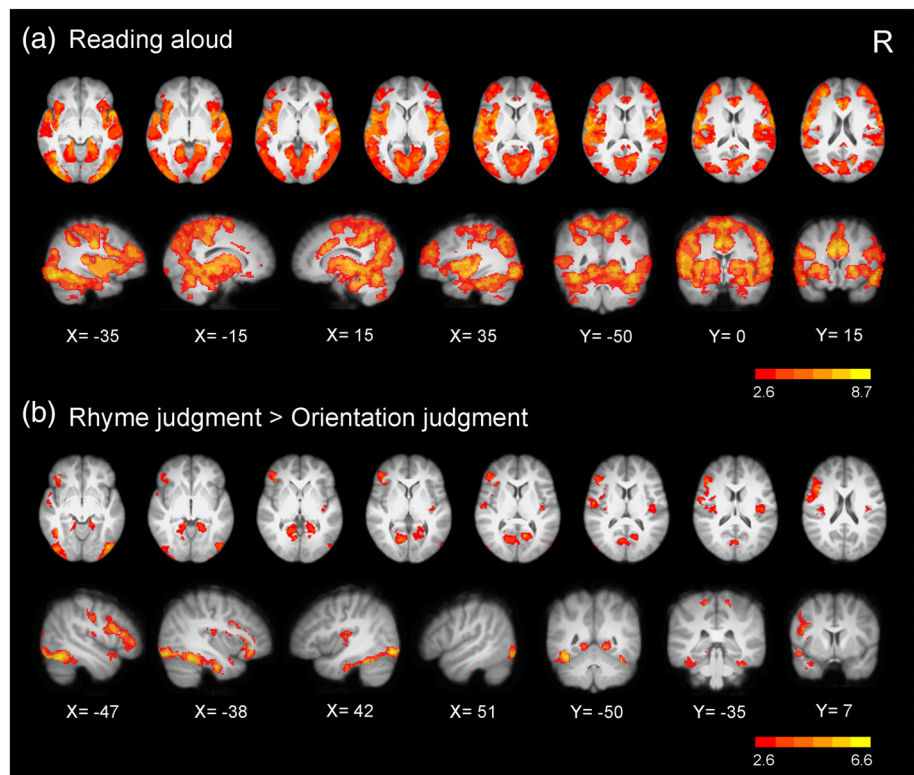


TABLE 2 Brain regions activated during the reading aloud task ($Z > 2.6$, corrected)

Regions	x	y	z	Z	Voxels
<i>Chinese character naming</i>					
Left middle frontal gyrus	-44	8	34	5.41	965
Right middle frontal gyrus	52	31	24	4.14	796
Left inferior frontal gyrus	-40	14	23	6.75	919
Right inferior frontal gyrus	43	32	14	4.22	665
Left precentral cortex	-46	-12	46	6.73	3713
Right precentral cortex	54	-3	38	6.68	3348
Left posterior superior temporal gyrus/supramarginal gyrus	-63	-17	-1	5.54	843
Right posterior superior temporal gyrus/supramarginal gyrus	51	-32	1	5.52	931
Left posterior cingulate gyrus	-10	-32	37	6.79	607
Right posterior cingulate gyrus	14	-38	-2	5.65	781
Left parahippocampal gyrus	-16	-32	-11	6.85	320
Right parahippocampal gyrus	20	-34	-8	6.88	292
Left middle temporal gyrus	-60	-54	10	5.43	850
Right middle temporal gyrus	60	-48	10	4.28	1522
Left inferior temporal gyrus	-52	-60	-12	6.68	698
Right inferior temporal gyrus	48	-56	-16	6.74	764
Left fusiform gyrus	-35	-48	-20	6.74	1815
Right fusiform gyrus	28	-36	-22	6.76	1689
Left lateral occipital lobe	-34	-89	-11	6.69	1814
Right lateral occipital lobe	48	-68	-12	6.75	1843

controlling for rating-based orthographic and semantic DSMs (all $p < .05$, see Table 3 and Figure S4). Five out of six ROIs (i.e., the left MFG, IFG, ITG, and bilateral FFG) also showed significant correlations

with model-based phonological DSM ($p < .05$, see Figure 5, Table 3, and Figure S4). Second, for the two ROIs (i.e., the left posterior STG and left anterior SMG) related to phonological processing of

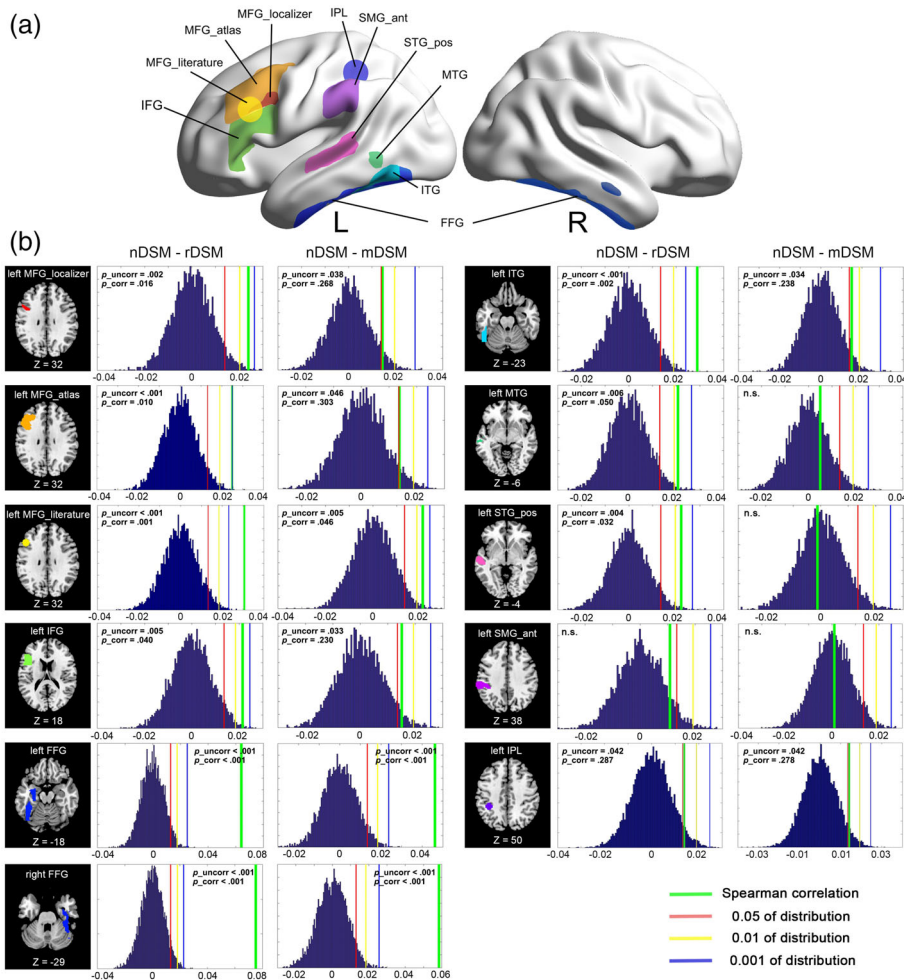


FIGURE 5 Permutation tests for ROI-based representational similarity analysis. (a) 11 ROIs are defined based on the localizer task, Harvard–Oxford atlas, and literature (Tan et al., 2005). (b) Histogram plots of permutation tests for correlations between neural DSMs and both the rating-based and model-based phonological DSM. nDSM, rDSM, and mDSM indicate neural dissimilarity matrix, rating-based phonological dissimilarity matrix, and model-based phonological dissimilarity matrix, respectively. The green line indicates the actual correlation between neural DSMs and phonological DSM. The red, yellow, and blue lines indicate the 0.05, 0.01, and 0.001 of the distribution, respectively. X-axis represents the correlation coefficients. FFG, fusiform gyrus; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; ITG, inferior temporal gyrus; MFG, middle frontal gyrus; MTG, middle temporal gyrus; STG_pos, posterior superior temporal gyrus; SMG_ant, anterior supramarginal gyrus; p_{corr} , FWE-corrected p value for all ROIs; P_{uncorr} , uncorrected p value for each ROI.

TABLE 3 Spearman correlations between neural DSMs and rating- and model-based phonological DSMs in the 11 predefined ROIs

Regions	nDSM – rDSM				nDSM – mDSM			
	Correlation		Control for O + S		Control for precentral gyrus		Correlation	
	Mean r	p	Mean r	p	Mean r	p	Mean r	p
Left MFG_localizer	.0239	.0018	.0264	.0011	.0190	.0114	.0144	.0378
Left MFG_atlas	.0250	<.001	.0298	<.001	.0154	.0289	.0138	.0458
Left MFG_literature	.0307	<.001	.0360	<.001	.0226	.0025	.0210	.0050
Left IFG	.0215	.0047	.0273	<.001	.0113	.0856	.0151	.0329
Left FFG	.0641	<.001	.0690	<.001	.0534	<.001	.0462	<.001
Right FFG	.0752	<.001	.0769	<.001	.0673	<.001	.0586	<.001
Left ITG	.0289	<.001	.0325	<.001	.0215	.0056	.0150	.0336
Left MTG	.0208	.0058	.0257	<.001	.0152	.0318	.0050	.2701
Left pos_STG	.0221	.0041	.0264	<.001	.0126	.0619	–.0011	.5543
Left ant_SMG	.0109	.0888	.0122	.0672	.0021	.3955	.0010	.4537
Left IPL	.0139	.0421	.0181	.0139	.0057	.2437	.0142	.0427

Note: nDSM, rDSM, and mDSM indicate neural dissimilarity matrix, rating-based phonological dissimilarity matrix, and model-based phonological dissimilarity matrix, respectively. Control for O + S means the correlation between the neural DSMs and the rating-based phonological DSM after controlling for the rating-based orthographic and semantic DSMs. Control for precentral gyrus means the correlation between the neural DSMs and the rating-based phonological DSM after controlling for the neural DSMs of precentral gyrus. Mean r represents the mean correlation coefficient of 27 participants. p represents the p values of the permutation tests. Significant p values are highlighted in bold. Abbreviations: MFG, middle frontal gyrus; FFG, fusiform gyrus; IFG, inferior frontal gyrus; ITG, inferior temporal gyrus; MTG, middle temporal gyrus; pos_STG, posterior superior temporal gyrus; ant_SMG, anterior supramarginal gyrus; and IPL, inferior parietal lobule.

alphabetic words, only the left posterior STG showed a significant correlation between the neural DSM and rating-based phonological DSM ($p < .01$). Neither region showed significant correlations with the model-based phonological DSM. Third, for the left MFG additionally defined based on Harvard–Oxford atlas and literature (Tan et al., 2005), the correlations were significant for both rating-based and model-based DSMs (all $ps < .05$). Finally, for the left inferior parietal lobule defined based on literature (Tan et al., 2005), the correlations were significant for both rating-based and model-based DSMs (all $ps < .05$).

We further applied FWE correction to the above permutation tests. After FWE correction, nine ROIs (i.e., the three left MFG ROIs, left IFG, left ITG, left MTG, left posterior STG, and bilateral FFG) survived for significance for rating-based phonological DSM (all $ps < .05$, see Figure 5), and three ROIs (i.e., the left MFG based on literature and bilateral FFG) survived for significance for model-based phonological DSM (all $ps < .05$, see Figure 5).

To elaborate on the function of the left MFG in character reading, we performed two additional analyses. First, the reading aloud task used in this study includes not only the phonological process in word identification but also the motor components of word production (i.e., articulation process) (Berken et al., 2015; Coltheart et al., 2001; Graves et al., 2010). To rule out the possibility that multi-voxel representations in left middle frontal gyrus reflect the articulation process inherent to the reading aloud task, we reran ROI-based RSA by including neural dissimilarity matrix (nDSM) in the precentral gyrus, which has been thought to be related to generating articulatory–motor phonological codes in speech production (Ekert et al., 2021; Hickok, 2012; Schwartz et al., 2012; Vigneau et al., 2006), as a covariate. Results showed that the left MFG defined by three different ways, bilateral FFG, left ITG, and left MTG still showed significant correlations between neural DSM and rating-based phonological DSM (all $ps < .05$; see Table 3 and Figure S4). Second, to examine the contribution of the left MFG to phonological processing of Chinese characters, we calculated partial correlations after controlling for the nDSM in the left IFG, a region that has been repeatedly reported in word reading (Dong et al., 2020; Jana et al., 2019; Kim et al., 2020; Liu et al., 2021; Tan et al., 2005; Tham et al., 2005; Wu et al., 2012), speech production (Basilakos et al., 2018; Flinker et al., 2015; Long et al., 2016; Mugler et al., 2018), and working memory (Basilakos et al., 2018; Ekert et al., 2021). Results showed that the left MFG defined based on the localizer task ($r = .0155$, $p = .028$), Harvard–Oxford atlas ($r = .0172$, $p = .0163$), and literature ($r = .0210$, $p = .0053$) still showed significant correlations between nDSM and rating-based phonological DSM.

The above results of ROI-based RSAs were confirmed by the whole-brain RSA. Specifically, whole-brain RSA on the rating-based phonological DSM revealed that phonological information of Chinese characters was represented in the left inferior frontal gyrus (extending to middle frontal gyrus), bilateral frontal pole, bilateral inferior temporal gyrus, and bilateral fusiform gyrus (extending to inferior occipital cortex) (see Figure S1a–d). A narrower but basically the same distribution of activation was observed for RSA on the model-based

phonological DSM relative to that on the rating-based phonological DSM (see Figure S1e,f). Taken together, these results suggest that phonological information was represented in the left prefrontal cortex and bilateral occipitotemporal regions during Chinese character reading.

4 | DISCUSSION

By using both univariate analysis (i.e., activation analysis) and multivariate analysis (i.e., RSA), the current study investigated the neural representation of phonological information during Chinese character reading. Univariate activation analysis revealed a widely distributed neural network for Chinese reading, including the bilateral inferior/middle frontal gyrus, lateral temporal gyrus, and fusiform gyrus. This network largely overlapped with the reading network reported in existing studies on Chinese characters (Dong et al., 2020; Jobard et al., 2003; Tan et al., 2005; Zhao et al., 2017; Zhou et al., 2018). More importantly, within this network, by associating neural patterns during character reading with phonological features of characters, multivariate RSA further identified brain areas directly associated with phonological processing, such as the left middle frontal gyrus, left inferior frontal gyrus, left inferior temporal gyrus, and bilateral fusiform gyrus. These results suggest that phonological information of Chinese characters is represented in brain regions in the ventral pathway and confirm the role of the left middle frontal gyrus in the phonological representation of Chinese characters.

Results of our study made two significant contributions to literature on the neural bases of Chinese reading. First, the present study provided direct neuroimaging evidence that the left MFG represents the phonology of Chinese characters by quantitatively establishing a connection between brain activation patterns and phonological features of Chinese characters. As mentioned in the Introduction, it is controversial whether the left middle frontal gyrus (MFG) is responsible for phonological processing (Cao et al., 2011; Chen et al., 2016; Liu et al., 2009; Tan et al., 2005) or general cognitive control (Courtney et al., 1998; Eayrs & Lavie, 2019; Hernandez et al., 2001; Wang et al., 2007) during reading Chinese characters. The results of the present study support the former view. First, the univariate activation analysis showed the involvement of the left MFG in both the rhyme judgment task and reading aloud task. Second, by correlating the neural DSM with both rating-based and model-based DSMs, RSA revealed that the left MFG showed significant correlations. Third, consistent correlations were found in the left MFG defined based on the localizer task, Harvard–Oxford atlas and literature (Tan et al., 2005), suggesting that phonological representation in the left MFG were not affected by its size or location. Finally, significant correlations were still observed in the left MFG after controlling for orthographic DSM, semantic DSM, nDSM in the precentral gyrus (presumably related to articulation–motor process), or nDSM in the left inferior frontal gyrus. These convergent findings support the view that the left MFG represents phonological information of Chinese characters during reading.

It should be noted that the left MFG found in the searchlight-based RSA was a bit anterior than the left MFG ROIs. This discrepancy in location could be accounted by methodological differences between the two approaches (Etzet et al., 2013). First, ROI analyses were performed in the native space, and less affected by individual differences in functional brain topography. In contrast, the data needed to be transformed to standard space to aggregate the results in the searchlight analysis. Consequently, imperfections in alignment may reduce the significance of results in the searchlight analysis (Etzet et al., 2013). Second, there were large differences in shape and size between ROI masks and searchlight cube, which might result in the location differences between the two analyses. Given the pros and cons of both approaches, we present both analyses to provide the reader with a more complete picture of the results.

In addition to the left MFG, we also found that the left inferior frontal gyrus (IFG) represented phonological information of Chinese Characters. The left IFG containing the traditional Broca's area is a key region for language comprehension and production (Fadiga et al., 2009; Nishitani et al., 2005). Much research has found that the left IFG is critical for reading words in both alphabetic and logographic languages (Dong et al., 2020; Jana & Gesa, 2019; Kim et al., 2020; Liu et al., 2021; Tan et al., 2005; Tham et al., 2005; Wu et al., 2012). Further research has revealed that the left inferior frontal gyrus is involved in the retrieval, manipulation, or selection of phonological representations (Booth et al., 2006; Cao et al., 2009, 2011; Siok et al., 2003; Tan et al., 2005). Consistent with previous findings, the present study found that the left IFG activated in both the rhyme judgment task (i.e., the localizer task) and reading aloud task. Furthermore, RSA on the two phonological DSMs revealed significant correlations in the left IFG, suggesting the left IFG represents phonological information of Chinese characters.

The second contribution of our study is to reveal involvement of regions in the ventral pathway (i.e., the left ITG, MTG, and bilateral FFG) in representing phonological information of Chinese characters. Cognitive models of word reading have proposed that phonology can be accessed through orthography-to-phonology mapping pathway (sub-lexical pathway) or semantics-mediated pathway (lexical pathway; Coltheart et al., 2001; Harm & Seidenberg, 2004). The dorsal (e.g., the dorsal part of IFG, SMG, and posterior STG) and ventral brain regions (e.g., the ventral part of IFG, ITG, and MTG) are thought to be responsible for sub-lexical and lexical pathways of phonological access, respectively (Cao et al., 2017; Jobard et al., 2003; Mei et al., 2015; Tan et al., 2005; Taylor et al., 2013). Previous neuroimaging studies have revealed that phonological processing of alphabetic languages depends more on sub-lexical pathway (Nosarti et al., 2010; Paulesu et al., 2000), whereas the logographic languages (e.g., Chinese) depend more on lexical pathway (Cao et al., 2017; Mei et al., 2015). Our study confirmed that phonological information of Chinese characters was represented in ventral brain regions (i.e., the left ventral part of IFG, ITG, MTG, and bilateral FFG) by associating neural patterns with phonological features of Chinese characters (i.e., RSA). Furthermore, phonological representations in those brain regions were still evident after controlling for orthographic and

semantic DSMs, suggesting those brain regions indeed represented phonological information during Chinese character reading. These results provide evidence for the particularity of Chinese character reading in terms of phonological representation.

In contrast to strong phonological representation in the ventral brain regions, phonological information of Chinese characters was less represented in the dorsal brain regions (i.e., the left temporoparietal cortex). Within the left temporoparietal cortex, our study found that only the left posterior STG showed significant correlation between the neural DSM and rating-based phonological DSM, neither the left STG nor the left SMG showed significant correlations with the model-based phonological DSM. The left temporoparietal cortex is thought to be responsible for grapheme-to-phoneme conversion (Glezer et al., 2016; Price, 2012; Pugh et al., 2001). Because reading Chinese characters relative to alphabetic words relies less on grapheme-to-phoneme conversion (Perfetti et al., 2005; Tan et al., 2005), the left temporoparietal cortex has been found to be less involved in phonological processing of Chinese characters (Bolger et al., 2005; Brennan et al., 2013; Cao et al., 2009; Oberhuber et al., 2016; Tan et al., 2003, 2005; Wu et al., 2012; Zhu et al., 2014). Therefore, our study only found weak phonological representation of Chinese characters in the left temporoparietal cortex. It should be noted that such weak phonological representation was observed even during a reading aloud task with relatively high demand for phonological processing, although there is evidence for enhanced involvement of the left posterior superior temporal gyrus in Chinese character reading as demand for phonological processing increases (Hu et al., 2010).

This study also explored phonological representation in the left IPL (a region more superior to the left SMG, and close to the left SPL). This region is thought to contain short-term storage of phonological codes, and has been found to be involved in Chinese character reading (Tan et al., 2005). One recent study further revealed that the left IPL plays an important role in processing sub-lexical components of Chinese characters (Liu et al., 2022). Nevertheless, we only observed relatively weak phonological representations in the left IPL (not significant after FWE correction). Given that its location is close to the superior parietal lobule (SPL), a region related to visuospatial processing of Chinese characters (Siok et al., 2009; Zhang et al., 2020), more evidence is needed to elaborate the function of the left IPL in Chinese character reading.

Two limitations should be discussed. First, this study examined phonological representation of Chinese characters using an explicit reading task (i.e., reading aloud task) because of its relatively high demand for phonological processing. However, this task requires a relatively high cognitive load and involves articulation process. Although we performed RSA by associating neural patterns in the left MFG with phonological information of Chinese characters to confirm phonological representation in the left MFG, and controlled for the potential confounding factors, such as the orthographic, semantic information of characters, and articulatory-motor phonological codes in speech production, our study cannot completely eliminate the effects of cognitive load and the articulation process on the neural patterns in the left MFG and cannot rule out the possibility that the left MFG might

carry different functions if the task demands semantic processing or other cognitive processes. Therefore, future studies should replicate our results by including the reading tasks varying in cognitive load, articulation process, and demand of semantic processing. Second, only 34 Chinese characters were included for the reading aloud task in this study. In other words, the number of materials used in the reading aloud task was relatively small, which might limit the generalization of our results to the process of all Chinese characters. Future studies should verify the results of our study by using a larger number of materials.

5 | CONCLUSION

To summarize, using both univariate analysis (i.e., activation analysis) and multivariate analysis (i.e., RSA), the present study revealed a widely distributed network for phonological processing of Chinese characters, including the bilateral prefrontal cortex, lateral temporal cortex, and occipitotemporal cortex. Among those regions, the left prefrontal (i.e., the left middle frontal gyrus, left inferior frontal gyrus) and bilateral occipitotemporal cortex (i.e., the bilateral fusiform gyrus, left inferior temporal gyrus) represented phonological information of Chinese characters during reading. These results suggest that phonological information of Chinese characters is represented in the ventral reading network.

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CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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