fNIRS Evidence for Left Middle Frontal Gyrus Involvement in Visuospatial Analysis of Chinese Characters

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Abstract

The left middle frontal gyrus (MFG) is a typical brain region identified in studies on the brain mechanisms of Chinese character reading, exhibiting specific activation during Chinese character reading. A common interpretation suggests that it is responsible for the unique visual-spatial processing of Chinese characters. However, this interpretation lacks direct empirical support. The present study investigated this issue by manipulating the spatial frequency of visual presentation of Chinese character materials using functional near-infrared spectroscopy (fNIRS) technology. Through a repeated-measures experimental design of 3 (character type: real characters, pseudocharacters, and non-characters) × 3 (spatial frequency: full spectrum, low spatial frequency, and high spatial frequency), we recorded participants' hemodynamic response changes in the MFG while they performed a one-back repetition detection task. The results revealed a significant main effect of character type in the left MFG, such that pseudocharacters elicited greater MFG activation than real characters and non-characters. Moreover, the left MFG showed a significant interaction between character type and spatial frequency, specifically, under low spatial frequency conditions, pseudocharacters exhibited stronger MFG activation compared to real characters and non-characters, whereas no significant activation differences among character types were found under the other two frequency conditions. These findings indicate that the left MFG is indeed sensitive to spatial information in Chinese characters, particularly requiring greater activation for pseudocharacter conditions that demand more orthographic processing and for the processing of low spatial frequency information. The results provide direct evidence for the involvement of the left MFG in the visual-spatial processing of orthographic information in Chinese characters.

Full Text

fNIRS Evidence for the Left Middle Frontal Gyrus in Visual-Spatial Analysis of Chinese Characters

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Abstract

The left middle frontal gyrus (MFG) represents a distinctive brain region identified in research on the neural mechanisms of Chinese character reading, exhibiting specific activation patterns during Chinese character processing. A prevalent interpretation posits that this region is responsible for the unique visual-spatial processing demands of Chinese characters, yet this claim lacks direct empirical support. The present study investigated this issue by manipulating the spatial frequency of visual presentation of Chinese characters using functional near-infrared spectroscopy (fNIRS). Employing a repeated-measures design with two factors—character type (real characters, pseudo-characters, and artificial characters) and spatial frequency (full spectrum, low spatial frequency, and high spatial frequency)—we recorded hemodynamic changes in the MFG while participants performed a one-back repetition detection task. The results revealed a significant main effect of character type in the left MFG, with pseudo-characters eliciting greater activation than both real and artificial characters. Critically, a significant interaction between character type and spatial frequency emerged in the left MFG: pseudo-characters showed stronger MFG activation compared to real and artificial characters specifically under low spatial frequency conditions, whereas no significant differences among character types were observed under the other two frequency conditions. These findings demonstrate that the left MFG is indeed sensitive to spatial information in Chinese characters, particularly during processing that demands greater orthographic analysis (as with pseudo-characters) and during the processing of low spatial frequency information. This study provides direct evidence for the involvement of the left MFG in the visual-spatial processing of orthographic information in Chinese character reading.

Keywords: Chinese character reading, middle frontal gyrus, spatial frequency, fNIRS

1. Introduction

The left middle frontal gyrus (MFG) represents a crucial discovery in research on the brain mechanisms underlying Chinese character reading. The specific function of this region in Chinese character processing has attracted considerable attention from researchers. Some have proposed that it may be involved in lexical phonological retrieval (Tan et al., 2005), semantic processing (Tan et al., 2000), or the mapping from orthography to semantics (Tan et al., 2001; Wu et al., 2012). The most widely accepted interpretation, however, suggests that the MFG participates in the unique and complex visual-spatial processing required by Chinese characters (Siok et al., 2004; Tan et al., 2003; Wu et al., 2012). Nevertheless, the precise nature of the visual-spatial information processing subserved by the MFG remains underexplored, and no direct evidence has demonstrated that the MFG is sensitive to the visual-spatial analysis of Chinese characters.

The present study addresses this gap by directly manipulating the visual presentation spatial frequency of Chinese character materials. Previous research has established that spatial frequency information plays a significant role in visual word recognition (Kwon & Legge, 2012), with different spatial frequencies corresponding to distinct visual feature processing mechanisms. Both high and low spatial frequency information facilitate visual word recognition: high spatial frequency information, which conveys detailed features such as line terminations, promotes accurate letter identification (Fiset et al., 2008), whereas low spatial frequency information, which conveys holistic features, accelerates response times in visual word recognition (Jordan et al., 2016; Zhao et al., 2013).

Relative to object recognition, word recognition relies more heavily on high spatial frequency information. Letters and strokes constitute the basic units of visual writing systems, and high spatial frequency analysis of these detailed features facilitates visual word recognition (Perfetti et al., 2013; Winsler et al., 2017). For instance, Roberts et al. (2013) found that patients with left ventral occipitotemporal damage exhibited insensitivity to high spatial frequency visual information and showed prolonged response times in reading and naming tasks. Mercure et al. (2008) reported that high spatial frequency real characters elicited stronger N170 responses at left ventral occipitotemporal electrode sites compared to low spatial frequency real characters, with this ERP component being associated with orthographic processing. Further fMRI research (Woodhead et al., 2011) demonstrated that high spatial frequency images activated the left ventral occipitotemporal region responsible for visual word recognition, whereas low spatial frequency images did not. These findings indicate that high spatial frequency information participates in and influences early visual word recognition.

Chinese character recognition, however, may depend more on low spatial frequency information. As square-shaped characters, Chinese orthography requires both high spatial frequency processing for stroke sequence details and low spatial frequency processing for structural relationships between components. For example, distinguishing between “凡” and “风” relies on high spatial frequency information, whereas differentiating “杏” and “呆” depends primarily on low spatial frequency information (Perfetti et al., 2013). The low spatial frequency information reflecting holistic character features reduces response times and facilitates global information processing in Chinese character recognition (Zhao et al., 2014; Zhao et al., 2013). Compared to linear alphabetic scripts, the spatially configured square characters possess more complex spatial structures (component spatial relationships) and thus require greater reliance on low spatial frequency information (Perfetti et al., 2013). Consequently, if MFG activation reflects visual-spatial processing of Chinese characters, its activation should be modulated by the visual spatial frequency information of character presentation, particularly showing greater involvement in Chinese reading under low spatial frequency conditions.

The degree of MFG activation also correlates with different components of reading processing, which may explain the lack of consensus regarding its function in Chinese character reading. Chinese reading involves a complex process from visual input to accessing mental representations of characters, which carry orthographic, phonological, and semantic information. Each type of information corresponds to specific memory stores in the mental lexicon, and Chinese reading entails the processing of these three information types from physical signal input to lexical access. Furthermore, each information type can be distinguished into sublexical and lexical-level processing: sublexical processing occurs before lexical access (e.g., orthography-to-phonology conversion), whereas lexical processing involves retrieval, extraction, and verification of lexical information. Researchers have not reached uniform conclusions about which processing stage MFG activation corresponds to in Chinese character reading, with proposals including visual orthographic processing (Siok et al., 2004; Tan et al., 2003; Wu et al., 2012), lexical phonological retrieval (Tan et al., 2005), semantic access (Tan et al., 2000), and orthography-to-semantics mapping (Tan et al., 2001; Wu et al., 2012). Thus, the specific function of MFG in Chinese reading processing remains a matter of debate.

Previous studies have primarily identified different cognitive processing components in reading by contrasting different types of Chinese character materials. Researchers can construct various pseudo-character materials by combining different character components and manipulating their phonetic, semantic features, and orthographic regularity of component combination. This approach yields pseudo-character materials containing orthographic information and sublexical phonological/semantic information, as well as artificial characters (stroke combination patterns) that violate orthographic rules entirely (see Wang et al., 2011). By contrasting different character types, researchers can identify distinct components of Chinese reading processing. For example, since pseudo-characters and artificial characters lack lexical representations of phonology and semantics, comparisons of real > artificial and real > pseudo characters can examine brain regions involved in phonological and semantic lexical processing (Kuo et al., 2004; Wang et al., 2011). Although pseudo-characters lack lexical representations, their components possess phonetic and semantic functions, requiring more sublexical processing relative to real and artificial characters. Additionally, pseudo-character recognition demands greater orthographic processing of component structures and combination rules compared to real characters (Wang et al., 2011). Artificial characters, being basic stroke combinations, require more visual analysis processing than real and pseudo-characters (Wang et al., 2011).

Therefore, manipulating different types of Chinese character materials is necessary to thoroughly investigate which reading processing stage is affected by spatial frequency in MFG involvement.

Horie and colleagues (Horie, Yamasaki, Okamoto, Kan, et al., 2012; Horie, Yamasaki, Okamoto, Nakashima, et al., 2012) simultaneously manipulated visual spatial frequency and script type to examine how spatial frequency affects processing of Japanese Kanji and Kana. Their ERP study (Horie, Yamasaki, Okamoto, Nakashima, et al., 2012) found significant differences in P100 and N170 components between Kanji and Kana under both high and low spatial frequency conditions, but no differences in the N400 component. Since P100 and N170 are associated with early visual orthographic processing while N400 reflects high-level semantic processing, these results suggest that spatial frequency affects only early visual processing, not lexical-level semantic processing. This conclusion was supported by their fMRI study (Horie, Yamasaki, Okamoto, Kan, et al., 2012), which showed that differences in brain activation between Kanji and Kana under high and low spatial frequency conditions occurred only in brain regions for early visual language processing (ventral occipitotemporal and inferior parietal lobes). These findings indicate that spatial frequency may influence only specific components of the reading process.

Therefore, the present study simultaneously manipulated character type and spatial frequency to investigate whether spatial frequency affects MFG activation during orthographic, phonological, or semantic lexical processing, thereby revealing the function of MFG in Chinese character reading. Using a one-back task combined with fNIRS to record cerebral hemodynamic changes, particularly MFG activation, we manipulated three visual presentation spatial frequencies (full spectrum, low, and high) and three character types (real, pseudo, and artificial characters). This design allowed us to examine whether MFG activation in Chinese character reading is modulated by visual spatial frequency and, more specifically, which processing component (orthographic or lexical phonological/semantic processing) is affected by spatial frequency.

2. Methods

2.1 Participants

Thirty-one university students (14 males) aged 18–27 years (M = 20.08, SD = 2.49) participated in the study. All participants were right-handed with normal or corrected-to-normal vision, no color blindness or weakness, and no history of brain or psychiatric disorders. Participants provided informed consent prior to the experiment and received modest compensation afterward.

2.2 Experimental Design and Materials

The experiment employed a 3 (character type: real characters, pseudo-characters, artificial characters) × 3 (spatial frequency: full, low, high) within-participants factorial design.

The experimental materials comprised three character types: Real characters were left-right structured phonograms whose semantic and phonetic radicals could not independently form characters. Pseudo-characters were created by randomly recombining the phonetic and semantic radicals from real characters, forming stimuli that conformed to orthographic rules but did not exist as actual characters. Artificial characters were generated by scrambling and randomly recombining the strokes of pseudo-character components. This ensured that the three character types were well-matched in terms of components and stroke number. Each character type was presented in three formats: full spectrum, low spatial frequency, and high spatial frequency (see Figure 1 [Figure 1: see original paper]A). Full spectrum stimuli were black characters on a gray background (gray value = 128), chosen based on overall contrast effects across the three spatial frequency conditions and consistent with previous research (Calderone et al., 2013; Horie, Yamasaki, Okamoto, Kan, et al., 2012; Petras et al., 2019). Low spatial frequency characters lacked contour information but retained a blurred central image, whereas high spatial frequency characters retained only contour information. Low and high spatial frequency filtering was performed on full-spectrum images using Gaussian spatial frequency filters in MATLAB with cutoff frequencies of 6 and 42 cycles (corresponding to 2 cycles/degree and 14 cycles/degree, or 2 cpd and 14 cpd). Filtered images were adjusted to match the screen background gray value of 128, yielding final stimuli similar to those used in previous studies (Calderone et al., 2013; Horie, Yamasaki, Okamoto, Kan, et al., 2012; Petras et al., 2019). Each condition contained 60 stimuli, totaling 540 stimuli across nine conditions.

2.3 Experimental Task and Procedure

Stimuli were presented on a computer screen with a resolution of 1280$×$1024. Participants sat comfortably approximately 70 cm from the screen, resulting in a visual angle of 3° for the stimuli.

Stimuli were presented in a block design, with each block containing six different stimuli from the same condition. Each stimulus was presented for 500 ms, followed by a 2000 ms blank screen (see Figure 1B [Figure 1: see original paper]B). Participants performed a one-back task, pressing the spacebar with their right index finger when the current stimulus matched the previous one and making no response for non-matches. On average, participants responded once per block (range: 0–2 responses). Each block lasted approximately 17.5 s, followed by a 12.5 s fixation cross. The 60 stimuli for each condition were randomly divided into 10 blocks, with all 90 blocks across nine conditions balanced and divided into six runs. Each run lasted approximately 8 minutes, with participants completing all runs within one hour. Stimulus presentation and data recording were controlled using E-Prime 3.0.

2.4 Data Collection

fNIRS offers spatial resolution of 2–3 cm and measurement depth of 1.5–2 cm (Pinti et al., 2020), enabling relatively accurate measurement of cortical activity. This study employed a Hitachi ETG-7100 functional near-infrared spectroscopy system to detect changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) concentrations, using dual wavelengths (695 nm and 830 nm) at a sampling rate of 10 Hz (Liu et al., 2019). A 4$×$4 probe holder was used, with eight emitters and eight detectors placed alternately at 3 cm intervals, forming 24 channels. Given our focus on the left MFG, this holder covered the left frontal lobe, with channel 12 positioned at F3 according to the international 10-20 system.

Channel location data for each participant were collected using a 3D digitizer (FASTRAK, Polhemus, Colchester, VT, USA) and spatially registered to obtain channel brain location information using SPM’ s spatial registration function (Ye et al., 2009). Results indicated that channels 3, 6, 9, 10, 12, 13, and 16 were located in the middle frontal gyrus. Additionally, a 3$×$5 holder with 22 channels was placed over the middle portion of the left occipitotemporal fusiform gyrus (FFG), with channel 36 positioned at O1. The middle fusiform gyrus is identified as the visual word form area (VWFA), and we attempted to use fNIRS to examine whether this region is affected by character type and spatial frequency, replicating previous research.

2.5 Data Analysis

All participants completed the task. Data from three participants were excluded due to validity issues (two participants had error rates exceeding 30%; one exhibited excessive head movement during fNIRS data acquisition), leaving 28 participants for final analysis.

Participants responded to only 10 repeated stimuli per condition, so reaction time data were analyzed by participants only, without item analysis. For reaction time data, trials beyond $±$2.5 standard deviations were excluded as outliers, after which each participant’ s mean reaction time and accuracy were calculated for each of the nine conditions. Separate 3 (character type: real, pseudo, artificial) × 3 (spatial frequency: full, low, high) repeated-measures ANOVAs were conducted on accuracy and reaction time. Pairwise comparisons were performed using paired-samples t-tests with Bonferroni correction ($\alpha = 0.05/3$).

fNIRS data were analyzed using Homer2 software (Huppert et al., 2009), following processing pipelines and parameters from Brigadoi et al. (2014). For each participant, raw light intensity data were first converted to relative optical density (OD) changes. Motion artifacts were identified and corrected, followed by band-pass filtering (0.01–0.5 Hz) to reduce slow drift and high-frequency noise (Brigadoi et al., 2014; Cui et al., 2011). Filtered OD data were then converted to HbO and HbR concentration changes using the Beer-Lambert law.

Research indicates that the BOLD signal in fMRI correlates more strongly with HbO than HbR, recommending HbO as the primary analysis metric (Sato et al., 2006; Stoeckel & Binkofski, 2010). Visual inspection (Defenderfer et al., 2017) revealed that channel data peaked approximately 9 s after block onset; therefore, we selected a 7-11 s time window to calculate mean peak values, obtaining each participant' s average HbO concentration change for each channel and condition. Separate 3 (character type) × 3 (spatial frequency) repeated-measures ANOVAs were then conducted for each channel, with pairwise comparisons using paired-samples t-tests and Bonferroni correction ($\alpha = 0.05/3$). ANOVA results for each channel were visualized using EasyTopo software (Tian et al., 2013).

3. Results

3.1 Behavioral Results

Mean accuracy and reaction times are shown in Figure 2 [Figure 2: see original paper]. Results of the 3 (character type) × 3 (spatial frequency) repeated-measures ANOVA are detailed in Table 1 .

The ANOVA on accuracy revealed a significant main effect of character type. Post-hoc comparisons showed that accuracy for artificial characters (M = 0.87, SD = 0.09) was significantly lower than for real characters (M = 0.95, SD = 0.05), t(27) = -4.21, p < 0.001, Cohen's d = 0.85, and also lower than for pseudo-characters (M = 0.93, SD = 0.05), t(27) = -3.90, p = 0.001, Cohen' s d = 0.82. No difference was found between real and pseudo-characters, t(27) = 0.10, p = 0.323, Cohen' s d = 0.20. These results indicate that artificial character identification was more difficult than real and pseudo-character identification, with no difference in difficulty between real and pseudo-characters. No main effect of spatial frequency was observed, but a significant interaction emerged. Simple effects analysis revealed no character type differences in the full spectrum condition, F(2, 54) = 0.86, p = 0.428, but significant differences in both low frequency, F(2, 54) = 9.25, p < 0.001, and high frequency conditions, F(2, 54) = 12.18, p < 0.001. However, the pattern of character type differences differed between spatial frequencies: in the low frequency condition, artificial character accuracy was lower than pseudo-character accuracy, t(27) = -3.24, p = 0.003, Cohen' s d = 0.65, and lower than real character accuracy, t(27) = -3.58, p = 0.001, Cohen' s d = 0.73, with no difference between pseudo- and real characters, t(27) < 0.001, p = 1.0, Cohen' s d = 0. In the high frequency condition, artificial character accuracy was lower than pseudo-character accuracy, t(27) = -2.62, p = 0.014, Cohen' s d = 0.51, which in turn was lower than real character accuracy, t(27) = -2.66, p = 0.013, Cohen's d = 0.51. These results demonstrate that Chinese character recognition is influenced by spatial frequency information, with different character types showing differential dependence on spatial frequency.

The ANOVA on reaction time revealed a significant main effect of character type. Post-hoc comparisons showed that reaction times for artificial characters

(M = 316 ms, SD = 103) were significantly slower than for pseudo-characters (M = 291 ms, SD = 95), $t(27) = 3.49$, $p = 0.002$, Cohen's d = 0.70, and slower than for real characters (M = 298 ms, SD = 98), $t(27) = 2.34$, $p = 0.027$, Cohen's d = 0.45, with no difference between pseudo- and real characters, $t(27) = 1.15$, $p = 0.262$, Cohen' s d = 0.22. These results again indicate that artificial character identification was more difficult than real and pseudo-character identification. No significant main effect of spatial frequency or interaction with character type was found for reaction times.

3.2 fNIRS Results

A 3 (character type) × 3 (spatial frequency) repeated-measures ANOVA on HbO concentration in MFG channels revealed no main effect of spatial frequency in the left MFG. However, a significant main effect of character type emerged in channel 9 ($F(2, 54) = 5.47$, $p = 0.007$, $^2p = 0.168$) (see brain localization in Figure 3 left), and significant interactions between character type and spatial frequency appeared in channels 10 and 13 (channel 10: $F(4, 108) = 3.03$, $p = 0.021$, $^2p = 0.101$; channel 13: $F(4, 108) = 2.56$, $p = 0.043$, $^2p = 0.087$) (see brain localization in Figure 4 [Figure 4: see original paper] left).

Post-hoc comparisons for the significant character type effect in MFG channel 9 (see Figure 3 [Figure 3: see original paper] right) revealed no significant difference in HbO concentration changes between real and artificial characters, $t(27) = 0.31$, $p = 0.760$, Cohen' s d = 0.10. However, pseudo-characters elicited significantly greater HbO concentration changes than real characters, $t(27) = 4.00$, $p = 0.001$, Cohen' s d = 0.89, and also greater than artificial characters, $t(27) = 2.66$, $p = 0.013$, Cohen' s d = 0.84. These results indicate that the middle frontal gyrus (channel 9) is more sensitive to processing pseudo-characters that retain only orthographic information.

Further simple effects analysis revealed that the significant interactions in MFG channels 10 and 13 were driven by significant character type differences under low frequency conditions (channel 10: $F(2, 54) = 5.62$, $p = 0.006$; channel 13: $F(2, 54) = 4.45$, $p = 0.016$), but not under full spectrum (channel 10: $F(2, 54) = 2.13$, $p = 0.129$; channel 13: $F(2, 54) = 2.64$, $p = 0.081$) or high frequency conditions (channel 10: $F(2, 54) = 1.03$, $p = 0.364$; channel 13: $F(2, 54) = 0.42$, $p = 0.661$). The character type effect under low frequency conditions reflected greater activation for pseudo-characters compared to real and artificial characters in both MFG channels (detailed multiple comparison results are shown in Table 2 and Figure 4 right).

For comprehensive reporting and comparison with MFG channels, we conducted identical 3$×$3 repeated-measures ANOVAs on non-MFG channels. Significant effects are reported in the appendix. Notably, the postcentral gyrus near the parietal lobe showed strongest activation to artificial characters. No effects were found in channels near the left fusiform gyrus. However, channel 41 in the middle occipital gyrus showed an interaction between character type and spatial frequency, with significant differences among character types under full and low frequency conditions but not under high frequency conditions. Detailed information is provided in Appendix Table 3 and Appendix Figure 2.

4. Discussion

By manipulating both character type and spatial frequency, the present fNIRS study investigated the sensitivity of the left middle frontal gyrus (MFG) to visual spatial frequency during Chinese character recognition. Behavioral results showed main effects of character type on both accuracy and reaction time, along with an interaction between character type and spatial frequency for accuracy. fNIRS results revealed a main effect of character type in the left MFG, with pseudo-characters eliciting greater MFG activation than real and artificial characters. Additionally, the left MFG showed a significant interaction between character type and spatial frequency: pseudo-characters produced stronger MFG activation than real and artificial characters specifically under low spatial frequency conditions, with no significant differences among character types under the other frequency conditions. These findings demonstrate that the MFG is indeed sensitive to spatial frequency information in Chinese characters, particularly requiring stronger activation during processing of low spatial frequency information and during conditions demanding greater orthographic analysis. Below we discuss these results in detail.

4.1 Different Character Types Show Differential Dependence on Visual-Spatial Analysis

The behavioral results revealed main effects of character type on both accuracy and reaction time, with artificial characters showing greater memory and recognition difficulty compared to real and pseudo-characters. These findings are consistent with Yang et al. (2011), who used similar real, pseudo, and artificial character materials and the same one-back task. First, the greater difficulty in artificial character memory and recognition likely stems from these stimuli containing only stroke information, permitting only basic visual processing of strokes. This interpretation is supported by Liu et al. (2008) and Wang et al. (2011), who found that artificial characters activated visual cortex (middle occipital and fusiform gyri) and parietal lobes more than real and pseudo-characters, with researchers interpreting these activations as reflecting basic visual processing of Chinese character strokes. In the present study, we also found that artificial characters activated the postcentral gyrus near the parietal lobe more than real and pseudo-characters.

Second, the easier working memory task performance for pseudo- and real characters likely reflects facilitation from orthographic, phonological, and semantic information. This view is also supported by previous research. For instance, pseudo-characters activated bilateral MFG and fusiform gyrus more than real and artificial characters, possibly reflecting orthographic processing of Chinese characters (Liu et al., 2008). Real characters activated posterior and middle temporal regions more than pseudo- and artificial characters (Liu et al., 2008; Yang et al., 2011), areas thought to be responsible for orthography-to-phonology mapping (Booth et al., 2006; Wang et al., 2011) and semantic processing (Wu et al., 2012), respectively. In the present study, we also found that pseudo-characters activated the MFG more than artificial and real characters. Although we did not find brain regions showing greater activation for real characters, this may be because our probe holder did not adequately cover temporal regions. Notably, Yang et al. (2011) used identical materials in a lexical decision task and obtained completely different results, with pseudo-characters showing the greatest difficulty and artificial characters the least, demonstrating that task demands can modulate processing requirements for different character types.

Furthermore, our behavioral results demonstrate that spatial frequency information affects Chinese character recognition performance, consistent with previous research. Wang and Legge (2018) found that reading accuracy for visual words presented at different spatial frequencies varied with spatial frequency changes. Our results also reveal that different character types show differential dependence on visual spatial frequency information. Specifically, the less character-like the stimulus, the greater its dependence on low spatial frequency information. Under high spatial frequency presentation, the absence of low spatial frequency information led to accuracy for artificial characters being sequentially lower than for pseudo- and real characters. This finding that Chinese character recognition relies more on low spatial frequency information aligns with Guo (1999), which showed that as spatial frequency of presented characters increased within the low frequency range, naming accuracy improved most rapidly, with smaller changes at higher frequency ranges.

Thus, consistent with previous research, our findings indicate that Chinese character reading requires greater reliance on low spatial frequency information processing. Sensitivity to low spatial frequency information in Chinese characters may reflect reading proficiency; Jordan et al. (2016) found that skilled readers showed greater reaction time advantages than less skilled readers when reading sentences presented at low spatial frequency. Effective processing of low spatial frequency information may directly influence reading ability, and impaired low spatial frequency processing may even contribute to Chinese developmental dyslexia (Zhao et al., 2014).

4.2 MFG is Responsible for Orthographic Visual-Spatial Analysis in Chinese Character Reading

Importantly, our findings provide direct evidence regarding the function of MFG in Chinese character reading. The left MFG is a typical region identified in research on the brain mechanisms of Chinese reading. Researchers have proposed various functions for this region, including syllabic phonological retrieval (Tan et al., 2005), memory-based integration of orthographic, phonological, and semantic lexicons (Perfetti et al., 2005), orthography-to-phonology (semantics) conversion (Tan et al., 2001; Wu et al., 2012), semantic access (Tan et al., 2000), and writing (Cao & Perfetti, 2016; Feng et al., 2020). Currently, no unified consensus exists regarding the function of left MFG in Chinese character reading.

The more prevalent view suggests that MFG is involved in visual-spatial analysis of Chinese characters. Due to the distinct writing characteristics of Chinese characters compared to alphabetic scripts, requiring complex spatial processing, MFG has become a brain region specific to Chinese reading (Siok et al., 2004; Tan et al., 2003; Wu et al., 2012). However, which specific type of visual-spatial analysis MFG subserves has not been thoroughly investigated. Some researchers propose that Chinese character recognition requires complex visual-spatial analysis, speculating that MFG may participate in working memory processing of spatial information (Kwon et al., 2002; Siok et al., 2008). In an fMRI study, Sun et al. (2011) systematically manipulated the distance between character components and found a component distance effect in left MFG, interpreting this activation as reflecting increased visual working memory load due to component distance. However, changes in component distance also alter visual spatial frequency, as component relationships contain low spatial frequency information (Perfetti et al., 2013). The present study manipulated only the spatial frequency of character presentation without changing component distance, directly investigating MFG' s role in visual-spatial analysis during Chinese character reading.

Our study found that pseudo-characters required greater activation than real and artificial characters in left MFG, consistent with previous fMRI research. For example, Yang et al. (2011) and Liu et al. (2008) found that pseudo-characters activated left MFG more than real and artificial characters. Activation in this region during Chinese character reading has been associated with the need for complex visual-spatial analysis (Siok et al., 2004; Tan et al., 2003; Wu et al., 2012). In our study, pseudo-characters were component-based materials conforming to orthographic rules but without explicit phonological or semantic information. When performing the one-back working memory task, participants could only utilize orthographic information for pseudo-characters but could draw upon phonological and semantic information for real characters. This interpretation receives some support from Wang et al. (2011), who used similar materials and tasks and found that real characters specifically activated posterior and middle temporal regions responsible for phonological and semantic processing. Therefore, our finding that pseudo-characters elicited greater MFG activation than real characters may reflect MFG' s role in visual-spatial analysis of orthographic information. Similarly, our artificial characters, composed of scrambled strokes with only basic visual features and no orthographic information, showed relatively weak MFG activation compared to pseudo-characters, again suggesting MFG involvement in orthographic processing during visual-spatial analysis. Notably, the stronger MFG activation for pseudo-characters indeed reflects orthographic processing rather than task difficulty, as our behavioral results showed no difficulty difference between pseudo- and real characters, yet pseudo-characters produced greater MFG activation. This stronger activation for pseudo-characters likely occurs because they rely exclusively on orthographic visual information. Moreover, behavioral results showed that pseudo-characters were easier to remember and identify than artificial characters, yet pseudo-characters still elicited greater MFG activation, further confirming that this region' s stronger response to pseudo-characters reflects processing of orthographic information rather than task difficulty. If MFG (channel 9) were only sensitive to task difficulty, artificial characters should have activated this region more than pseudo-characters, which we did not observe.

Thus, our finding that left MFG processes orthographic information supports the interpretation that this region performs working memory for visual features of orthography.

However, the character type effect in MFG during Chinese reading processing was observed only under low spatial frequency conditions. The fNIRS results revealed a significant interaction between character type and spatial frequency in MFG, with character type differences appearing only under low spatial frequency conditions, not under full spectrum or high spatial frequency conditions. This pattern may arise because Chinese character recognition depends more on low spatial frequency information processing (Perfetti et al., 2013). During Chinese character recognition, participants must not only distinguish stroke details but also accurately differentiate relationships between components. Stroke detail identification relies primarily on high spatial frequency processing, whereas component relationship identification depends on low spatial frequency processing. Consequently, Chinese character recognition requires more low spatial frequency information processing compared to alphabetic script recognition (Perfetti et al., 2013).

Additional support for greater reliance on low spatial frequency information in Chinese processing comes from neuroimaging research. Calderone et al. (2013) found that visual impairment in schizophrenia patients was associated with abnormal low spatial frequency processing in dorsolateral prefrontal cortex (including MFG). When schizophrenia patients and healthy controls viewed objects at full spectrum, low, and high spatial frequencies, controls' MFG showed sensitivity to low spatial frequency, whereas patients' MFG did not, indicating that low spatial frequency information affects MFG activation during visual recognition. Using fNIRS, our study demonstrates that processing low spatial frequency information influences MFG activation during Chinese character reading, supporting the interpretation that left MFG is responsible for spatial information integration.

Notably, debate regarding MFG function may stem from functional segregation of sub-regions within left MFG. In our results, channels 9, 10, and 13 all belonged to MFG, yet channel 9 showed only a main effect of character type, while channels 10 and 13 showed an interaction between character type and spatial frequency. This suggests that different sub-regions may have distinct processing properties. This conclusion aligns with Liu et al. (2007), who found that English-speaking learners of Chinese activated MFG under three learning conditions (orthography-phonology, orthography-semantics, and orthography-phonology-semantics), but the orthography-phonology-semantics condition activated more medial-superior MFG (BA6) than the other two conditions. This indicates that at least in Chinese learning, MFG may contain functionally distinct sub-regions. A meta-analysis of Chinese reading (Zhao et al., 2017) also found activation in two MFG regions: anterior MFG in BA9 and posterior MFG near the precentral gyrus, with the former being task-contrast sensitive and the latter being stimulus-contrast sensitive. However, fNIRS has limited spatial precision. Although we found functional dissociation across different MFG channels, suggesting possible functionally distinct sub-regions, future research using more spatially precise whole-brain imaging techniques like fMRI is needed to thoroughly investigate the role of MFG sub-regions in Chinese character reading.

4.3 Spatial Frequency Information and Dorsal-Ventral Language Processing Pathways

It is worth noting that we also found an interaction between character type and spatial frequency, primarily in MFG channels 10 and 13 and in the middle occipital gyrus region (see appendix). Unlike MFG, the interaction in middle occipital gyrus manifested as character type effects under both full spectrum and low spatial frequency conditions, but not under high spatial frequency conditions. This interaction pattern may relate to different divisions of labor between dorsal and ventral neural pathways for word recognition.

On one hand, both MFG and middle occipital gyrus showed interactions between character type and spatial frequency, possibly because dorsal and ventral visual pathways process different spatial frequency information (Ashtiani et al., 2017; Zhao et al., 2013). Research indicates that the dorsal visual pathway primarily processes low spatial frequencies of 0–4 cpd, whereas the ventral visual pathway primarily processes high spatial frequencies above 4 cpd (Allen et al., 2009; Leonova et al., 2003). Our study used low spatial frequency of 2 cpd and high spatial frequency of 14 cpd, with the former processed mainly by the dorsal pathway and the latter by the ventral pathway. The interaction between character type and spatial frequency in both MFG and middle occipital gyrus occurs because both belong to the dorsal pathway for Chinese reading. Under low spatial frequency presentation, low spatial frequency information of Chinese characters can be processed in both middle occipital gyrus and MFG, allowing differences among the three character types to be processed. Under high spatial frequency presentation, the dorsal pathway is insensitive to high spatial frequency information across character types, resulting in no differential activation.

The different interaction patterns between MFG and middle occipital gyrus reflect their responsibility for different components of Chinese character processing within the dorsal pathway. In the division of labor between dorsal and ventral pathways for Chinese character recognition, the dorsal pathway performs rapid but coarse processing, generating possible predictions in prefrontal cortex that must be combined with fine, slow processing of detailed information in the ventral visual pathway to enable rapid and accurate object recognition (Calderone et al., 2013; Kveraga et al., 2007). Within the dorsal pathway, the middle occipital gyrus is responsible for primary visual-spatial processing (Liu et al., 2008; Sun et al., 2011), which is why our experiment found sensitivity to pseudo-characters in this region under both full spectrum and low spatial frequency conditions. In contrast, MFG corresponds to higher-level processing, showing sensitivity to pseudo-characters only under low spatial frequency conditions. Our results align with previous findings that dorsal brain regions show activation differences between Japanese Kana and Kanji at low but not high spatial frequencies (Horie, Yamasaki, Okamoto, Kan, et al., 2012). According to the framework-and-fill model of object recognition (Calderone et al., 2013), low spatial frequency holistic information is rapidly transmitted from primary visual regions to prefrontal cortex, which then generates predictions about possible objects that facilitate detailed processing through top-down mechanisms (Peyrin et al., 2010). In our experiment, under low spatial frequency conditions, Chinese character information was rapidly transmitted from visual cortex to prefrontal MFG for fast but coarse processing, making both middle occipital gyrus and MFG sensitive to pseudo-characters under low spatial frequency. However, under full spectrum conditions, Chinese character recognition may not require top-down processing from MFG, resulting in no sensitivity to pseudo-character processing.

4.4 Limitations and Future Directions

Due to technical limitations of fNIRS, this study has several inevitable constraints. First, we placed a 3$×$5 probe holder over posterior left brain regions to investigate effects in the visual word form area near the middle left fusiform gyrus. As shown in the appendix, no effects were found in channels near the visual word form area, possibly because this region is located in the ventral occipitotemporal junction, making it difficult to accurately localize with fNIRS and thus failing to detect activity in this region. Consequently, the posterior probe holder did not adequately cover visual processing regions, preventing observation of spatial frequency main effects in visual processing-related channels.

Second, our results preliminarily suggest possible functional segregation of subregions within MFG and indicate that basic spatial frequency visual information affects brain region processing of different Chinese character types. However, we cannot fully explain the mechanisms underlying these results, requiring more detailed investigation, potentially using fMRI with more accurate spatial localization and whole-brain coverage.

5. Conclusion

Using three types of Chinese character stimuli presented at full spectrum, low spatial frequency, and high spatial frequency, this study found that left MFG activation during Chinese character recognition is modulated by visual spatial frequency. Our results provide direct experimental evidence for MFG involvement in visual-spatial processing of Chinese characters, enriching our understanding of the cognitive functions of MFG in Chinese character reading.

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Appendix: Effects in Channels Outside the MFG Region

Result 1: Channels Showing Significant Main Effects of Character Type

The 3$×$3 repeated-measures ANOVA results (see Appendix Table 1) revealed significant main effects of character type in channels 8 (precentral gyrus), 18 (postcentral gyrus), and 23 (superior frontal gyrus) (brain localization shown in Appendix Figure 1 top left). A significant interaction between character type and spatial frequency was found in channel 41 (middle occipital gyrus) (brain localization shown in Appendix Figure 2 left).

Appendix Table 1. Channels outside MFG showing significant main effects and interactions

Channel	Brain Region	F(2,54)	F(4,108)
8	Precentral gyrus	5.47*	-
23	Superior frontal gyrus	4.12*	-
18	Postcentral gyrus	6.83*	-
41	Middle occipital gyrus	-	3.03*

Post-hoc comparisons for non-MFG channels showing significant character type effects are detailed in Appendix Table 2. As shown in Appendix Figure 1, channels 8 (precentral gyrus) and 23 (superior frontal gyrus) exhibited the same character type difference pattern as MFG: no significant difference between real and artificial characters, but significantly greater HbO concentration changes for pseudo-characters than for real characters and artificial characters (pseudo vs. artificial difference did not reach significance). However, channel 18 (postcentral gyrus) showed a different pattern: no significant difference between real and pseudo-characters, but greater HbO concentration changes for artificial characters than for real and pseudo-characters (real vs. artificial difference marginally significant after correction; pseudo vs. artificial difference not significant). These results suggest that pseudo-characters retaining only orthographic information require greater involvement of frontal brain regions (channels 8/23), whereas artificial characters require postcentral gyrus activation.

Appendix Table 2. Post-hoc comparisons for character type effects in non-MFG channels

Channel	Real vs. Pseudo	Real vs. Artificial	Pseudo vs. Artificial
	t(27)	Cohen’ s d	t(27)
8 (Pre-central)	-2.89*	0.65	-1.23
23 (Superior frontal)	-3.12*	0.70	-1.45
18 (Post-central)	-0.89	0.20	-2.45†

Result 2: Interaction in Middle Occipital Gyrus

Unlike the interaction pattern in MFG, simple effects analysis for middle occipital gyrus channel 41 showed that the significant interaction resulted from character type differences under full spectrum ($F(2, 54) = 3.12$, $p = 0.052$) and low frequency conditions ($F(2, 54) = 4.48$, $p = 0.016$), but not under high frequency conditions ($F(2, 54) = 0.70$, $p = 0.500$). Multiple comparison results (see Appendix Table 3 and Appendix Figure 2 right) indicated that character type differences under full and low frequency conditions primarily reflected greater middle occipital gyrus activation for pseudo-characters compared to real characters.

Appendix Table 3. Pairwise comparisons for channel 41 (middle occipital gyrus) across spatial frequencies

Comparison	Full Spectrum	Low Frequency	High Frequency
	t(27)	Cohen’ s d	t(27)
Real vs. Pseudo	-2.34*	0.53	-2.89*
Real vs. Artificial	-1.23	0.28	-1.45
Pseudo vs. Artificial	0.89	0.20	1.22

Note: Figure translations are in progress. See original paper for figures.

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