



# Dissociation of Writing Processes: A Functional Magnetic Resonance Imaging Study on the Neural Substrates for the Handwritten Production of Chinese Characters

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## Abstract

■ Writing is an important way to communicate in everyday life because it can convey information over time and space, but its neural substrates remain poorly known. Although the neural basis of written language production has been investigated in alphabetic scripts, it has rarely been examined in nonalphabetic languages such as Chinese. The present functional magnetic resonance imaging study explored the neural substrates of handwritten word production in Chinese and identified the brain regions sensitive to the psycholinguistic factors of word frequency and syllable frequency. To capture this, we contrasted neural activation in “writing” with “speaking plus drawing” and “watching plus drawing.” Word frequency (high, low) and syllable frequency (high, low) of the picture names were manipulated.

Contrasts between the tasks showed that writing Chinese characters was mainly associated with brain activation in the left frontal and parietal cortex, whereas orthographic processing and the motor procedures necessary for handwritten production were also related to activation in the right frontal and parietal cortex as well as right putamen/thalamus. These results demonstrate that writing Chinese characters requires activation in bilateral cortical regions and the right putamen/thalamus. Our results also revealed no brain activation associated with the main effects of word frequency and syllable frequency as well as their interaction, which implies that word frequency and syllable frequency may not affect the writing of Chinese characters on a neural level. ■

## INTRODUCTION

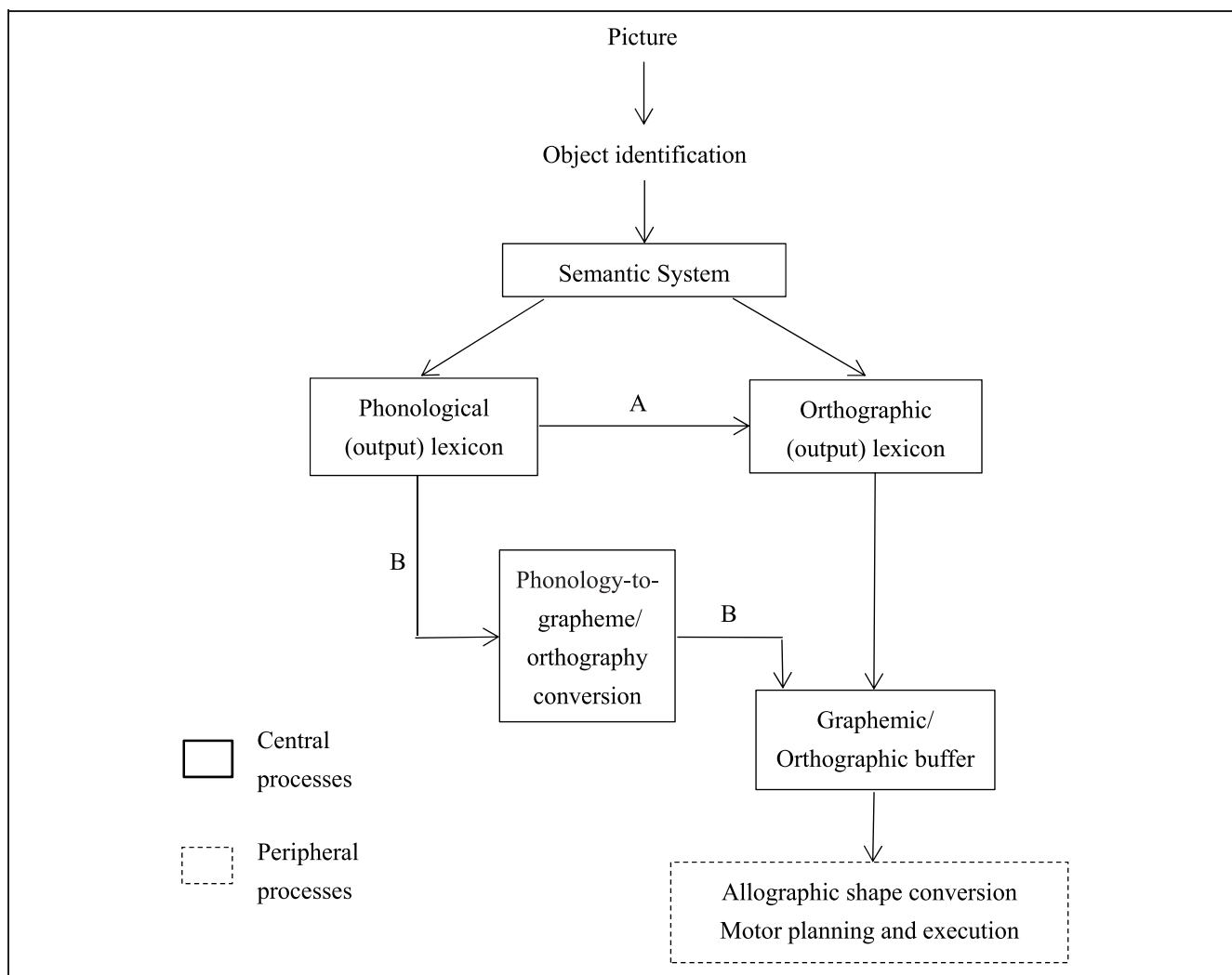
Written language production, an everyday form of communication, requires the coordination of multiple cognitive, linguistic, and motor processes. Existing psycholinguistic models (e.g., Beeson & Rapcsak, 2002; Rapp & Caramazza, 1997; Roeltgen & Heilman, 1985) have outlined the various processes involved in written language production, especially in written picture naming (e.g., Bonin, Peereman, & Fayol, 2001). As described in Figure 1, the first processing level of written picture naming is object identification, and it spreads activation to semantic systems. The activated semantic representations flow in parallel to phonological and orthographic lexicons where phonological and orthographic word forms are retrieved, respectively. Then, the activated phonological and orthographic word forms propagate to a graphemic buffer (or an orthographic buffer in Chinese; see Han, Zhang, Shu, & Bi, 2007) in which abstract representations corresponding to individual graphemes (or logographs in Chinese; see Han et al., 2007) are temporarily held and their positions are specified. The orthographic information maintained active in the graphemic/orthographic buffer can be either retrieved from the

orthographic lexicon (a lexical route, Arrow A) or assembled through phonology-to-grapheme/orthography conversion (a sublexical route, Arrow B). Finally, these orthographic representations are translated into writing by selecting allographs as well as planning and executing motor programs. An important distinction is often made to discern the central and peripheral processing components of writing (see Figure 1), although these processes are highly integrated. The cognitive architecture depicted in Figure 1 therefore provides a theoretical foundation to investigate the neural basis of written language production via neuropsychological and neuroimaging approaches.

Information regarding the neural substrates of processing components of written language production comes from neuropsychological studies in individuals with various forms of agraphia and functional neuroimaging studies in neurologically intact individuals, which has demonstrated that a left-hemisphere-dominated neural network is responsible for the writing in alphabetic languages such as English or French. We review these findings here to delineate the network that has been established for alphabetic languages.

Individuals with lexical agraphia have difficulty in spelling irregular words because of a damaged orthographic lexicon but can spell words with regular spelling and nonwords via phoneme–grapheme corresponding rules. Lexical agraphia is associated with lesions to the left

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**Figure 1.** Working model of written picture naming (Bonin et al., 2001).

extrasyllabic temporo-parietal cortex including posterior middle/inferior temporal gyrus, fusiform gyrus (BA 37), and/or angular gyrus (BA 39; e.g., Rapp & Caramazza, 1997; Behrmann, 1987; Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981), suggesting that these brain regions are responsible for the storage of orthographic knowledge in the lexicon. Neuroimaging studies have generally corroborated these findings. For instance, Beeson et al. (2003) reported significant activation in the left posterior inferior temporal cortex (BA 37/20) reflecting retrieval of orthographic word forms in writing English. Previous studies have also shown that activation in the left midfusiform gyrus and posterior inferior frontal gyrus is involved in lexical–orthographic processing for both writing and reading (Purcell, Turkeltaub, Eden, & Rapp, 2011; Rapp & Lipka, 2011).

Neuropsychological evidence regarding the possible localization of phonological processing of writing comes from phonological agraphia, a syndrome characterized by having difficulty in spelling unfamiliar words or pronounceable nonwords because of a damage to the

phoneme–grapheme conversion, but with preserved ability to write familiar words by relying on the lexical route (Penniello et al., 1995; Alexander, Friedman, Loverso, & Fischer, 1992; Roeltgen, Sevush, & Heilman, 1983). The critical lesion sites in phonological agraphia involve the left superior temporal gyrus (BA 22), the anterior supramarginal gyrus (BA 40), and/or insula (Beeson & Rapcsak, 2002; Marien, Pickut, Engelborghs, Martin, & De Deyn, 2001; Alexander, Friedman, et al., 1992), indicating that these brain regions support phonological processing in writing. A fMRI study by Sugihara, Kaminaga, and Sugishita (2006) also reported left supramarginal gyrus (BA 40) activation when writing Japanese phonograms (kana) relative to naming silently. Because participants could use the sublexical route to write Japanese kana because of its straightforward phoneme–grapheme conversion, the left supramarginal gyrus (BA 40) is therefore assumed to be involved in sublexical processing for writing.

With regard to the graphemic buffer, neuropsychological studies have found that a damage to the graphemic

buffer leads to phonologically implausible spelling, showing a characteristic pattern of errors consisting of additions, substitutions, or transpositions of single/multiple letters (Cloutman et al., 2009; Beeson & Rapcsak, 2002). Brain lesions associated with the graphemic buffer deficits are primarily associated with left frontal and parietal areas including the precentral gyrus and premotor cortex (BA 4/BA 6) and the postcentral gyrus (BA 2/BA 3; Cloutman et al., 2009; Beeson & Rapcsak, 2002). Furthermore, an fMRI study by Rapp and Dufor (2011) has shown that activation in the left superior frontal sulcus (BA 6) and superior parietal lobe (BA 7) is sensitive to the manipulation of word length that indexes orthographic working memory where orthographic information is temporarily maintained, suggesting that these regions are responsible for the graphemic buffer.

Peripheral processes of writing are associated with a widespread left frontal–parietal network including the dorsal premotor cortex and superior parietal lobule (BA 7). In neuropsychological studies with apraxic agraphia, a syndrome characterized by poor letter formation because of defective motor control of handwriting, damage has been reported in the left superior parietal lobule (BA 7), superior portions of the supramarginal gyrus, angular gyrus (BA 39; Beeson & Rapcsak, 2002; Alexander, Fischer, & Friedman, 1992), and SMA (Watson, Fleet, Gonzalez-Rothi, & Heilman, 1986). An fMRI study by Beeson et al. (2003) confirmed the critical role of the left frontal–parietal network associated with the peripheral writing processes. In particular, left superior parietal lobule (BA 7) activation seems to be associated with the representation, serial selection, and production of letter shapes (Rapp & Dufor, 2011), and it may also play a role in a high-level interface between language and motor areas during writing (Planton, Jucla, Roux, & Démonet, 2013; Segal & Petrides, 2012). The left dorsal premotor cortex is involved in the processing of translating orthographic information into appropriate hand movements (Beeson et al., 2003; Menon & Desmond, 2001).

The above literature focuses mainly on writing in alphabetic scripts (e.g., English, French), yet relatively little work has investigated the neural substrates of writing non-alphabetic languages, especially Chinese, a writing system that differs remarkably from alphabetic languages. Specifically, unlike the linear structure of an alphabetic word constructed by a sequence of letters, a Chinese character has a square configuration that consists of radicals formed by strokes, leading to a high level of visual–spatial structure in its orthographic form. A Chinese character’s phonology is also defined at the syllabic, rather than phonemic or segmental, level, which means there are no parts of the character corresponding to phonological segments such as phonemes (Tan et al., 2000). Thus, the regular or quasi-regular grapheme-to-phoneme correspondence existing in all alphabetic languages should be the orthography-to-phonology correspondence in Chinese instead. However, the orthography-to-phonology

correspondence is somewhat arbitrary, as there are a large number of homophones in Chinese with shared phonology (or pronunciation/pinyin) but have their own orthographic forms. These characteristics of Chinese imply that writing Chinese characters may rely on different neural substrates from alphabetic languages.

Consistent with this, a few studies have found that Chinese writing requires the involvement of brain regions not only in the left hemisphere but also in the right hemisphere (e.g., Yang et al., 2019; Cao & Perfetti, 2016; Lin, Xiao, Shen, Zhang, & Weng, 2007). For instance, Lin et al. (2007) observed activation in bilateral middle frontal gyri, superior parietal lobules, and superior temporal gyri involved in a dictation-for-mental writing task in Chinese. A more recent study has found that writing Chinese characters is associated with activation in the bilateral superior/inferior frontal gyri, precentral gyri, fusiform gyri, cerebellum, and left precuneus, when contrasting writing-to-dictation with drawing circles (Yang et al., 2019). However, these studies only characterized the neural correlates underlying the whole processing but did not distinguish the neural substrates of specific processing components (e.g., phonology or orthography) of Chinese writing. These studies also did not interpret the cognitive roles of the brain regions in the right hemisphere that might be important for writing Chinese characters. Importantly, no work has examined brain activation associated with Chinese handwritten production by using a written picture-naming paradigm that represents a typical and straightforward way of writing words. Written picture naming requires strong involvement of semantic constraints because it involves conceptual preparation and the connections from semantic to orthography/phonology, whereas these processes are less involved in the writing-to-dictation task (Bonin, Méot, Lagarrigue, & Roux, 2015). The investigation on the written picture naming would provide insights into the extent to which these written production tasks rely on similar or different neural substrates.

The present study, therefore, explored the neural substrates of the processing components behind Chinese writing using a written picture-naming paradigm that is cognitively different from the paradigms used in previous studies (e.g., imagined writing in Cao & Perfetti, 2016; Lin et al., 2007; writing-to-dictation in Yang et al., 2019) to some extent. Brain hemodynamic (BOLD) responses were measured during three tasks that differentially engaged linguistic and motor processes: writing down picture names (“writing”), watching a grid while drawing circles (“watching plus drawing”), and naming pictures silently while drawing circles (“speaking plus drawing”). The comparison of “writing” with “watching plus drawing” would identify brain activation related to the retrieval of orthographic information from the semantic activation of a pictured object and the motor planning/execution of hand movements necessary for writing Chinese characters. The comparison of “writing” with “speaking plus drawing” would reveal brain activation associated with

the retrieval of orthographic word forms but eliminate the common activation related to shared processes such as object recognition, semantic processing, phonological processing, and general motor programming associated with drawing circles. In combination with the existing literature, these comparisons allow us to demonstrate the universal principles guiding the organization of the writing system in the brain.

As mentioned earlier, the arbitrary orthography-to-phonology correspondence means that a Chinese character has relatively clear dissociation between its orthography and phonology (Tan, Feng, Fox, & Gao, 2001; Tan & Perfetti, 1998). This provides an ideal way to examine the neural substrates of orthographic and phonological processes of writing Chinese characters. To this end, the current study manipulated the word frequency (high, low) and syllable frequency (high, low) of picture names, which indexed orthographic and phonological processes in Chinese writing, respectively.

The word frequency effect refers to the finding that picture names with a low word frequency are produced slower than those with a high word frequency (Wingfield, 1968; Oldfield & Wingfield, 1965). Neuropsychological studies have supported the claim that the word frequency effect in writing indexes the robustness of the orthographic lexicon (also referred to as orthographic long-term memory representations), as the disruption to the orthographic lexicon is characterized by a specific pattern of spelling errors that words with a low word frequency are more likely to be disrupted than those with a high word frequency (Goodman & Caramazza, 1986). Existing evidence shows that the word frequency effect in the writing of alphabetic languages is associated with brain activation in the left inferior temporal gyrus/fusiform gyrus (BA 37), left inferior frontal gyrus, and/or left angular gyrus (Rapp & Dufor, 2011; Beeson & Rapcsak, 2002). However, only two studies so far have explored the neural substrates of word frequency effects in the writing of Chinese characters. Chen, Chang, Chen, Lin, and Wu (2016) did not observe any brain activation specific to word frequency effect in a Chinese character form judgment task, whereas Yang et al. (2018) reported activation in the bilateral superior/middle/inferior frontal gyri, superior/inferior parietal lobules, and fusiform gyri associated with word frequency effect in a copying Chinese characters task. The inconsistent findings may be because of the variation in writing tasks. The present study thus seeks to identify the brain regions associated with the word frequency effect, which would uncover the neural mechanism of orthographic processing components, especially orthographic lexicon, during Chinese writing.

The syllable frequency effect refers to the finding that picture names with a low syllable frequency are produced slower than those with a high syllable frequency (Levelt, Roelofs, & Meyer, 1999; Levelt & Wheeldon, 1994). The syllable frequency effect has primarily been investigated in spoken language production, and it is ascribed to the

retrieval of stored syllables from the mental syllabary during phonetic encoding in alphabetic languages (Laganaro & Alario, 2006; Levelt et al., 1999). However, it is assumed that the syllable frequency effect in Chinese speech production should occur at an earlier stage, namely, phonological encoding stage, as syllables are the first selectable phonological units in spoken Chinese that are retrieved from the mental lexicon in the initial stage of phonological encoding (O'Seaghdha, Chen, & Chen, 2010). Because written and spoken word production recruit shared semantic and phonological processes (Bonin & Fayol, 2000; Bonin, Fayol, & Gombert, 1998), we assume that the syllable frequency effect in Chinese written production should also occur at earlier phonological processing (i.e., phonological lexicon in Figure 1). The current study therefore provides a first insight into the neural correlates of the syllable frequency effect in the writing of Chinese characters, which would further reveal the neural basis of phonological processing components, especially phonological lexicon, during writing.

The interaction between word frequency and syllable frequency also provides some insights into a long-standing issue in written language production: whether phonological information constrains the retrieval of orthography in writing. The phonological mediation hypothesis assumes that accessing orthographic codes depends on prior retrieval of phonological codes (Luria, 1970; Geschwind, 1969). By contrast, the orthographic autonomy hypothesis assumes that orthographic information can be accessed directly from semantic representations without phonological involvement (Miceli, Benvegno, Capasso & Caramazza, 1997; Rapp, Benzing, & Caramazza, 1997). Although each of the hypotheses has been supported by chronometric data and event-related potentials in alphabetic (e.g., English, French) and nonalphabetic (e.g., Chinese) languages (e.g., Zhang & Wang, 2014; Afonso & Álvarez, 2011; Damian, Dorjee, & Stadthagen-Gonzalez, 2011; Bonin et al., 2001; Bonin, Fayol, & Peereman, 1998), no investigation on brain activation has been conducted to contribute to this argument. The two hypotheses therefore make different predictions for the manipulations in the current study: The phonological mediation hypothesis (Luria, 1970; Geschwind, 1969) predicts that word frequency should interact with syllable frequency, whereas the orthographic autonomy hypothesis (Miceli et al., 1997; Rapp et al., 1997) predicts that word frequency effect should not be influenced by syllable frequency.

To sum up, the present study investigated the writing-specific brain regions in Chinese by using a written picture-naming paradigm with three tasks: writing, watching plus drawing, and speaking plus drawing. The primary purpose of this study was to identify which brain areas support Chinese handwritten production. We predicted that the activation of classic brain regions (e.g., the left superior/middle frontal gyri, the left superior/inferior parietal lobules, and the left inferior temporal gyrus/fusiform gyrus) involved in the writing of alphabetic

languages would be replicated in Chinese writing. Because Chinese characters involve more complex visual–spatial processing than alphabetic languages because of their square configuration, we also expected that some brain regions in the right hemisphere cortex (e.g., the right superior/inferior parietal lobules) would be involved in Chinese handwritten production.

The secondary purpose of the present study was to identify specific brain regions associated with the orthographic lexicon and phonological lexicon by manipulating the word frequency (high, low) and syllable frequency (high, low) of to-be-named pictures, shedding light on how word and syllable frequencies interrelate. We predicted that word frequency effect would be associated with the activation in the left inferior temporal gyrus and/or fusiform gyrus and that syllable frequency effect would be related with the activation in the left superior temporal gyrus. In addition, if phonological codes influence the retrieval of orthographic information in the writing of Chinese characters, we predicted that word frequency effect would show different patterns of brain activation in the high- and low-syllable-frequency conditions.

## METHODS

### Participants

Twenty-three right-handed native Chinese speakers (11 men and 12 women) from Renmin University of China participated in the study. The sample size is similar to that used in most fMRI studies on written language production (e.g., the range of the sample size is 8–20 participants; see Planton et al., 2013; Purcell, Napoliello, & Eden, 2011) and seemed appropriate for our study. All participants were university students with a mean age of 22 years (range: 18–25 years). They reported normal or corrected-to-normal vision, normal reading and writing abilities, and no hearing impairments and history of neurological or psychiatric disorders. They provided written informed consent and received a payment of ¥160 for their participation. The study was approved by the ethics review board in the Institute of Psychology of Chinese Academy Sciences.

### Stimuli and Tasks

Sixty pictures with monosyllabic names (see Appendix A, Table A1) were selected from the database of black-and-white line drawings (Zhang & Yang, 2003) with language norms in standard Mandarin Chinese. For the picture names, word frequencies were obtained from the Chinese Frequency Dictionary (Beijing Language Institute, 1986). Syllables in Chinese are simple units, and each syllable requires one of five tone values (i.e., four primary tone values and an atonal value; see O’Seaghdha et al., 2010). Chinese characters’ phonology (or pronunciation/pinyin) is constructed from a rather small inventory of syllable units, which means each syllable is homophonic with

multiple free and bound morphemes (Packard, 2000). Because a Chinese character’s pronunciation (e.g., 家 /jia1/) corresponds to one syllable (/jia/), the syllable has many homophones with the same tone value (i.e., /jia1/) and different tone values (i.e., /jia2/, /jia3/, and /jia4/). Syllable frequency is defined as the frequency of occurrence of content-specified syllable-sized units (Laganaro & Alario, 2006); syllable frequencies in Chinese were thus calculated by summing the word frequencies of one syllable without counting tones. Of the picture names, 30 have a high word frequency ( $\geq 130$  per million) and the other 30 have a low word frequency ( $\leq 47$  per million). Among high- and low-word-frequency picture names, half had a high syllable frequency ( $\geq 2558$  per million) and the other half had a low syllable frequency ( $\leq 1479$  per million). Independent *t* tests showed a significant difference between the names with high and low word frequency,  $t(58) = 9.42$ ,  $p < .001$ , and also a significant difference between the names with high and low syllable frequency,  $t(58) = 9.57$ ,  $p < .001$ , but no difference in any of the following psycholinguistic attributes: number of orthographic neighborhoods, number of strokes, name agreement, image familiarity, image agreement, and image complexity (see Appendix A, Table A2). Eight additional pictures were selected from the same database as practice stimuli. Word frequency (high, low) and syllable frequency (high, low) were both treated as within-participant variables.

As noted in the Introduction, a target writing task and two control tasks were designed: (1) a “writing” task, in which participants were asked to write down picture names; (2) a “speaking plus drawing” task, in which participants were asked to name pictures covertly while drawing circles; and (3) a “watching plus drawing” task, in which participants were asked to look at a  $3 \times 3$  square grid, comparable to the black-and-white line drawings, while drawing circles. There were 60 trials corresponding to 60 pictures with varying word frequency (high, low) and syllable frequency (high, low) in the “writing” task and in the “speaking plus drawing” task, respectively, and 20 trials in the “watching plus drawing” task. Note that we designed 20 trials for the “watching plus drawing” task to avoid a potential fatigue effect because of a long scanning session. This was inspired by previous work by Rapp and Dufor (2011) and the claim that the stability of the fMRI hemodynamic responses can reach stability across repeated samples when averaging about 25 trials (Huettel & McCarthy, 2001). In addition, 20 trials of a null event were also included in which participants were asked to look at a fixation cross.

The 160 trials were presented in a blocked fashion, where five trials from each task formed a block, resulting in 32 blocks in total. The order of blocks was counterbalanced across participants. A unique order of stimuli was created for each participant with the Mix program (van Casteren & Davis, 2006), with the constraints that the same task was not presented in consecutive blocks, and the names of five pictures within a block were not

semantically (i.e., from the same semantic category), phonologically (i.e., share the same syllable), or orthographically (i.e., share the same radicals) related. Stimulus presentation was programmed using E-Prime 2.0 software ([www.pstnet.com/eprime.cfm](http://www.pstnet.com/eprime.cfm)).

## Procedure

The whole experiment included three stages: familiarization, a behavioral test, and a test during fMRI scanner. At the first two stages, participants were tested individually in a soundproof room where they sat at a comfortable viewing distance in front of the computer. During the familiarization stage, participants were asked to familiarize themselves with all pictures by viewing each picture for 3500 msec with the correct name printed below. Then, they were asked to write down the name of each picture within 5000 msec, followed by the feedback of the correct name of the picture presented for 2000 msec. After this, participants were asked to correct their wrong responses by repeatedly writing the right names for five times.

During the behavioral test, participants' writing responses and written latencies (i.e., the intervals from onset of picture presentation to initial contact of the pen on the writing surface) were recorded by a Wacom Intuos A4 graphic tablet with a Wacom inking digitizer pen. Participants were asked to hover the stylus just above the corresponding line on the sheet of paper, which would avoid an arm movement when starting writing; they were asked to write their responses as quickly and accurately as possible without seeing their writing responses. The behavioral test included eight practice trials (two trials per block, four blocks in total) and 160 experimental trials (five trials per block, 32 blocks in total). To avoid fatigue effects on writing performance, participants took a short break of 16 sec after completing the first 80 experimental trials. In each block, a written instruction appeared on the screen to inform participants about the task they would be performing. Then, each of pictures in a block was presented on the screen for 5000 msec subsequently during which participants made corresponding responses, followed by a fixation cross with a variable intertrial interval of 2.5–7.5 sec. Because the experimental program in the behavioral test was the same as that in the fMRI test but with a different order of stimuli presentation within and across participants, the variable intertrial interval would allow us to treat individual trials for each task as separate events during the later fMRI image statistical analysis (see also Segal & Petrides, 2012). An example of experimental tasks is shown in Figure 2. Because all participants' writing accuracies were above 97% for the behavioral test, it is assumed that they performed this writing task equivalently during the fMRI scanning stage (see also Segal & Petrides, 2012, for an identical procedure).

Before entering the fMRI scanner, participants received a short training session of about 10 min to familiarize themselves with the requirements of the test and imitate

what they would do in the scanner. They were instructed to hold a pencil gently and write their responses on the same spot on a piece of paper (i.e., one word was written on top of the other) without seeing their responses, which would avoid hand and wrist movements as well as additional cognitive activities such as monitoring the spatial layout of the paper sheet. During the scanning stage, participants were provided a piece of paper resting at their right side next to their thigh and a pencil with which to make writing responses, they were instructed to write picture names and draw circles in their normal writing style at the same location of the paper, and their performance was real-time monitored via a computer camera. As noted earlier, the experimental program during this stage was as same as that of behavioral test consisting of eight practice trials (two trials per block) and 160 experimental trials (five trials per block), but with a different order of stimuli presentation.

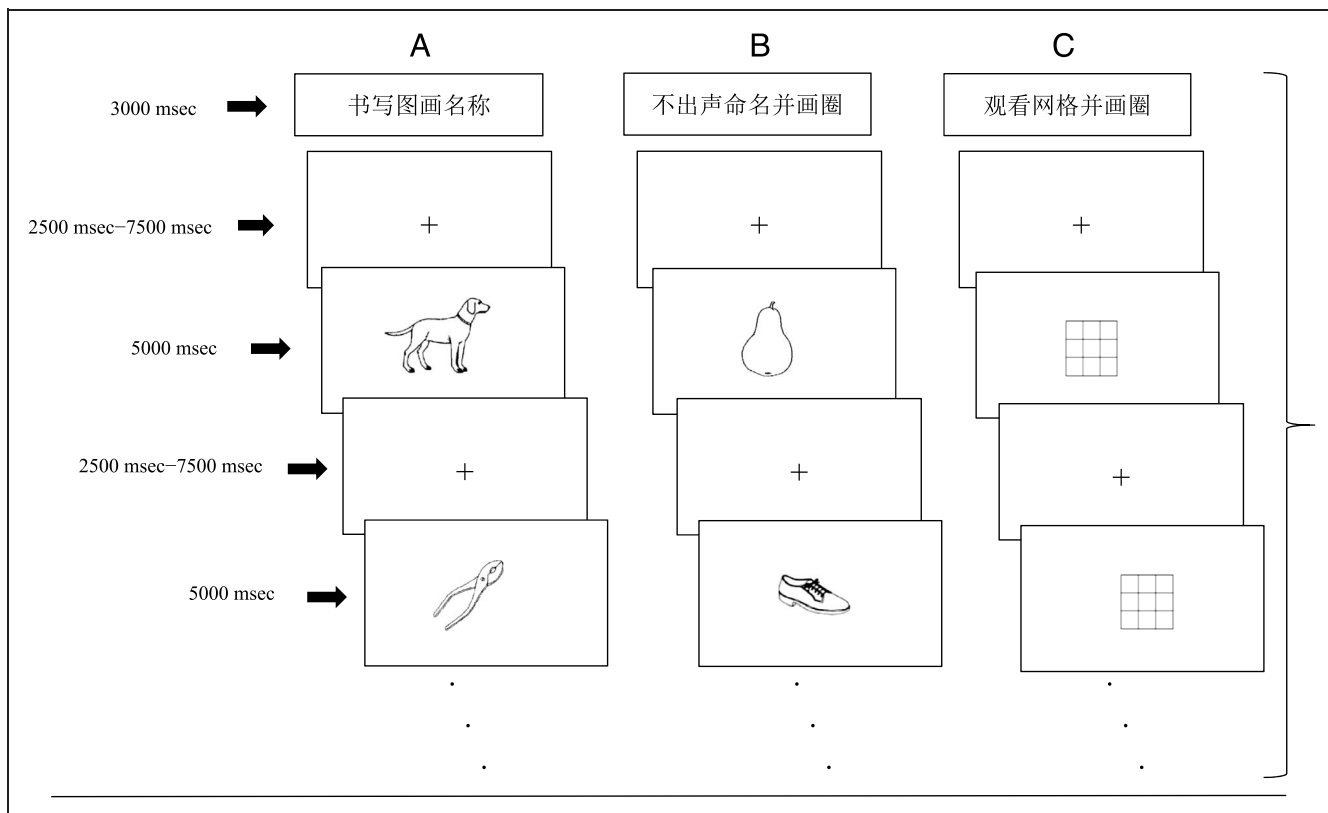
## fMRI Data Acquisition

Participants were positioned in a 3.0-T MRI scanner (GE Discovery MR750) after screening for metal objects, and they were ensured to be in a comfortable writing position before the start of the scanning session. Noise-canceling earplugs and headphones were used to protect against the noise from the MRI machine. Small foam cushions were placed on the sides of the participant's head to minimize head movement. The paper was placed at the right side near the participants' thighs, allowing them to write gently with the pencil provided. Visual stimuli were displayed through a projector with a translucent screen and viewed through an angled mirror.

An EPI sequence was employed to acquire functional images with the following parameters: repetition time = 2000 msec, echo time = 30 msec, flip angle = 80°, field of view = 220 × 220 mm, and matrix = 64 × 64. Each volume was composed of 36 slices covering the whole brain (slice thickness = 3 mm with a 0.5-mm gap, voxel size = 3 × 3 × 3 mm<sup>3</sup>). To allow the magnetic resonance signal to reach equilibrium, a 6-sec dummy scan (i.e., three repetition times) was acquired at the beginning of the functional scan. The total scanning time was about 30 min. High-resolution, T1-weighted anatomical images were obtained using a 3-D spoiled-gradient-echo sequence with the following parameters: angle = 8°, field of view = 256 × 256 mm, matrix = 256 × 256, and slice thickness = 1 mm.

## MRI Data Analysis

All preprocessing and statistical analysis of the fMRI data were performed using the software package SPM8 ([www.fil.ion.ucl.ac.uk/spm/](http://www.fil.ion.ucl.ac.uk/spm/)) in MATLAB (The Mathworks, Inc.). The anatomical scan was normalized to Montreal Neurological Institute (MNI) standard space (Collins et al., 1998). The EPI images were corrected for head motion



**Figure 2.** Three tasks designed in the experiment: (A) writing down picture names (“writing”), (B) naming pictures covertly while drawing circles (“speaking plus drawing”), and (C) watching a square grid while drawing circles (“watching plus drawing”).

by realignment of each scan to the first image, coregistered with the anatomical scan, normalized with the same parameters used to normalize the anatomical scan, and then smoothed with a  $6\text{-mm}^3$  full-width-half-maximum Gaussian kernel. To ensure that the fMRI data were not confounded by excessive head motion, participants were included only if their motion in the vector of the  $x$ ,  $y$ , or  $z$  direction was less than one voxel (3 mm). The data from two participants therefore had to be discarded, and the data from the remaining 21 participants were used for further analysis.

The first- and second-level statistical analyses were performed by using the general linear model (GLM) approach (Friston et al., 1994). At the first level, we modeled the hemodynamic activity for each task (writing, speaking plus drawing, and watching plus drawing) with the canonical hemodynamic response function for each participant. To account for confounds because of stimulus-timed movements, the model also included the six head motion parameters (roll, pitch, yaw,  $x$ ,  $y$ , and  $z$ ) into the GLM as regressors of noninterest. Two contrasts were created to reveal areas of activation associated with cognitive processes of interest in writing: The first was “writing > watching plus drawing,” which would isolate brain activation related to the retrieval of orthographic information from semantic activation of a pictured object and the motor planning/execution of hand movements

necessary for writing Chinese characters. The second contrast was “writing > speaking plus drawing,” which would reveal brain activation associated with the retrieval of orthographic representations but remove the common activation related to shared processes such as object recognition, semantic processing, phonological processing, and general motor programming associated with drawing circles.

The images of the two contrasts were brought to the second level in a random effects group analysis to perform population-level inferences (Penny & Holmes, 2007). Whole-brain  $t$  test contrasts were conducted using a threshold of  $p < .05$  voxel-wise corrected using false discovery rate (FDR) correction. Anatomical localization of the group statistical maps was determined by using the automated anatomical labeling toolbox (Tzourio-Mazoyer et al., 2002) and the SPM Anatomy Toolbox (Eickhoff et al., 2005; [www.fz-juelich.de/ime/spm\\_anatomy\\_toolbox](http://www.fz-juelich.de/ime/spm_anatomy_toolbox)). The significant cluster peaks were reported in MNI coordinates and corresponding Talairach (TAL) coordinates (Talairach & Tournoux, 1988) calculated by Ginger ALE (Fox et al., 2013), and their local maxima were reported with respective  $Z$  values.

To examine the neural substrates sensitive to the factors of word frequency (high, low; HWF, LWF) and syllable frequency (high, low; HSF, LSF), we modeled four conditions (HWF\_HSF, HWF\_LSF, LWF\_HSF, LWF\_LSF) in the

“writing” task at the first level with the canonical hemodynamic response function. The six head motion parameters (roll, pitch, yaw,  $x$ ,  $y$ , and  $z$ ) were also included in the GLM as regressors of noninterest. To analyze the group effects, the four contrast images per participant were entered into a second-level random effects analysis using a  $2 \times 2$  flexible factorial design, which consisted of word frequency (high, low) and syllable frequency (high, low). The same strict statistical threshold as the task contrast ( $p < .05$ , FDR corrected) was applied for this analysis.

## RESULTS

### Behavioral Results

Trials with incorrect writing responses, null responses, and writing latencies shorter than 300 msec or longer than 2000 msec were excluded from the 21 participants’ data, eliminating 1.36% of trials. Data points that were more than 3  $SD$ s below or above the participants’ mean writing latencies were also removed, eliminating 1.86% of trials. Descriptive statistics are shown in Table 1.

Because accuracy was at ceiling, a repeated-measures analysis of variance was conducted only on the measurement of written latencies. The results showed a significant main effect of word frequency [ $F_1(1, 20) = 11.25, p = .003, \eta_p^2 = 0.36; F_2(1, 56) = 12.91, p = .001, \eta_p^2 = .19$ ] and a significant main effect of syllable frequency [ $F_1(1, 20) = 7.58, p = .012, \eta_p^2 = .28; F_2(1, 56) = 4.12, p = .047, \eta_p^2 = .07$ ]. The interaction between word frequency and syllable frequency was not significant [ $F_1(1, 20) = 11.25, p = .28, \eta_p^2 = .05; F_2(1, 20) = 1.18, p = .28, \eta_p^2 = .02$ ].

### Brain Activation Associated with Task Contrasts

#### *Writing > Watching plus Drawing*

Comparing “writing” with “watching plus drawing” removes activation related to object identification and general motor control of the pencil but retains activation associated with the processes including the retrieval of semantic, phonological, and orthographic representations as well as the motor procedures necessary for writing Chinese characters. As shown in Table 2 and Figure 3A,

the “writing > watching plus drawing” contrast resulted in significant frontal lobe activation in the left hemisphere with two peak clusters: One cluster showed extensive activation in the left SMA (BA 6) extending to the superior frontal gyrus (BA 6); the other was in the precentral gyrus (BA 9) and extended to the middle frontal gyrus (BA 6) and inferior frontal gyrus (BA 44). This contrast also revealed significant left parietal cortex activation with two peak clusters: One cluster was in the left superior parietal lobule (BA 7) extending to the inferior parietal lobule (BA 7) and angular gyrus (BA 39); the other was in the left supra-marginal gyrus (BA 40).

#### *Writing > Speaking plus Drawing*

Comparing “writing” with “speaking plus drawing” reflects orthographic processing and specific motor procedures necessary to Chinese handwritten production. Similar to the “writing > watching plus drawing,” the contrast of “writing > speaking plus drawing” also showed significant left frontal and parietal activation, but with some cortical and subcortical activation in the right hemisphere. As shown in Table 2 and Figure 3B, there was significant activation in bilateral precentral gyri (BA 6). Activation in the bilateral parietal cortex was identified with two peak clusters: One was in the left superior parietal lobule (BA 7) extending to the superior frontal gyrus (BA 6) and post-central gyrus (BA 4); the other was in the right inferior parietal lobule (BA 40) extending to the superior parietal lobule (BA 7). In addition, right subcortical structures such as putamen and thalamus were also activated in the “writing > speaking plus drawing” contrast.

### Correlation between Brain Activation for the Writing Task and Written Latencies

To examine the relation of activation with real handwriting processing, we conducted a correlation analysis between the brain activation for the “writing” task and written latencies. A threshold of  $p < .05$  voxel-wise corrected using FDR correction was applied for this correlation. Results showed significantly negative correlations between the written

**Table 1.** Mean Written Latencies (msec) and Accuracy (%) Per Condition

		Written Latencies ( $M \pm SD$ )	Accuracy
High WF	High SF	855.41 $\pm$ 88.15	99.7
	Low SF	865.74 $\pm$ 105.65	99.7
Low WF	High SF	885.09 $\pm$ 102.08	100
	Low SF	922.85 $\pm$ 112.08	97.8

$M$  refers to mean value, and  $SD$  refers to standard deviation. WF and SF refer to word frequency and syllable frequency, respectively.



**Table 2.** List of Anatomical Regions, Volumes, Maximal Z Values, and Peak Coordinates for the “Writing > Watching plus Drawing” and “Writing > Speaking plus Drawing” Contrasts

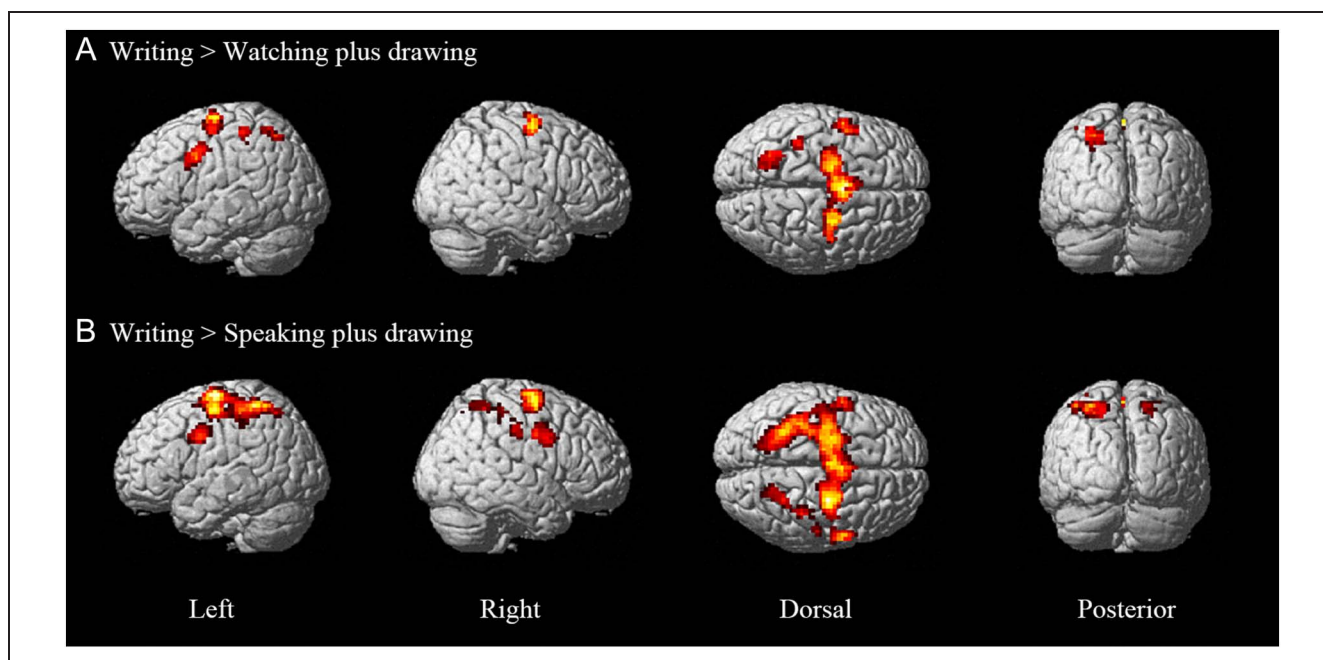
Anatomical Region (Estimated Brodmann's Area)	Volume (voxels)	$Z_{max}$	MNI Coordinates			TAL coordinates		
			<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
<i>Writing &gt; watching plus drawing</i>								
Frontal lobe								
L SMA (BA 6)	693	5.39	-6	0	63	-7	-7	60
L SMA (BA 6)		4.79	-6	6	51	-7	-1	50
L superior frontal gyrus (BA 6)		4.58	-18	-9	69	-19	-16	65
L precentral gyrus (BA 9)	113	3.98	-48	6	39	-46	1	39
L middle frontal gyrus (BA 6)		3.83	-54	0	45	-52	-5	43
L inferior frontal gyrus (BA 44)		3.80	-42	6	30	-40	1	31
Parietal lobe								
L superior parietal lobule (BA 7)	124	4.15	-27	-60	54	-27	-62	47
L inferior parietal lobule (BA 7)		3.84	-27	-51	54	-27	-54	47
L angular gyrus (BA 39)		3.76	-27	-60	39	-27	-61	33
L supramarginal gyrus (BA 40)	33	3.61	-36	-36	57	-35	-40	51
<i>Writing &gt; speaking plus drawing</i>								
Frontal lobe								
L precentral gyrus (BA 6)	90	4.14	-57	0	36	-54	-5	35
R precentral gyrus (BA 6)	98	4.97	60	3	33	54	-2	35
R precentral gyrus (BA 6)		3.84	60	-3	45	54	-9	45
Parietal lobe								
L superior parietal lobule (BA 7)	1992	5.78	-27	-54	60	-27	-57	52
L superior frontal gyrus (BA 6)		5.12	-21	-12	69	-21	-19	64
L postcentral gyrus (BA 4)		4.93	-33	-33	57	-32	-37	52
R inferior parietal lobule (BA 40)	242	3.65	39	-33	54	34	-37	50
R superior parietal lobule (BA 7)		3.61	27	-51	57	23	-54	51
R superior parietal lobule (BA 7)		3.51	18	-57	60	15	-60	53
Other								
R putamen	30	3.23	30	-15	9	27	-17	11
R thalamus		3.21	12	-21	9	10	-22	10
R thalamus		3.13	21	-9	9	18	-11	12

$n = 21$  ( $p < .05$ , FDR corrected). L = left; R = right.

latencies and activation with three peak clusters, where shorter written latencies (i.e., better performance) were correlated with greater intensity activation in the left Rolandic operculum (BA 41), the right paracentral lobule (BA 5), and the right lingual gyrus extending into the left calcarine (BA 30). The correlation results are presented in Table 3 and Figure 4.

### Brain Regions Specific to the Effects of Word Frequency and Syllable Frequency

A flexible factorial design with factors of Word Frequency (high, low) and Syllable Frequency (high, low) was performed to explore the neural substrates of orthographic and phonological processes in writing. We did not find

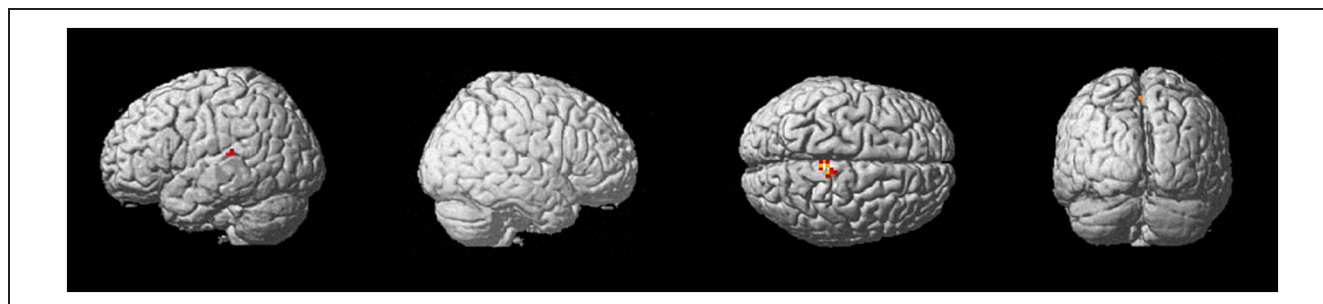


**Figure 3.** Whole-brain contrast maps for three tasks. Each was projected on a standard rendered SPM template brain. Only clusters surpassing 30 voxels are shown. (A) Map of clusters for the “writing > watching plus drawing” contrast ( $p < .05$ , FDR corrected). (B) Map of clusters for the “writing > speaking plus drawing” contrast ( $p < .05$ , FDR corrected).

**Table 3.** List of Anatomical Regions, Volumes, Maximal Z Values, and Peak Coordinates for the Negative Correlation of Written Latencies with Brain Activation for the “Writing” Task

Anatomical Region (Estimated Brodmann’s Area)	Volume (voxels)	$Z_{max}$	MNI Coordinates			TAL Coordinates		
			$x$	$y$	$z$	$x$	$y$	$z$
Frontal lobe								
L Rolandic operculum (BA 41)	35	4.62	-42	-24	12	-40	-25	12
R Paracentral lobule (BA 5)	34	4.33	3	-36	60	1	-41	55
R Paracentral lobule (BA 5)		4.28	9	-30	69	6	-36	63
R Paracentral lobule (BA 5)		3.76	6	-33	51	4	-37	47
Occipital lobe								
R Lingual gyrus	62	5.01	6	-54	0	4	-52	-1
L calcarine (BA 30)		4.97	-3	-57	3	-4	-55	2

$n = 21$  ( $p < .05$ , FDR corrected). L = left; R = right.



**Figure 4.** Whole-brain map for the negative correlation between written latencies and brain activation for the “writing” task ( $p < .05$ , FDR corrected). The activation was projected on a standard rendered SPM template brain. Only clusters surpassing 30 voxels are shown.

any brain activation associated with the main effects of Word frequency and Syllable frequency as well as their interaction.

## DISCUSSION

In this fMRI study, which to our knowledge is the first of its kind to be conducted in Chinese, we used a written picture-naming paradigm to investigate the brain basis of Chinese handwritten production. As in alphabetic languages (e.g., Rapp & Dufor, 2011; Sugihara et al., 2006), central processes and specific motor procedures necessary for Chinese handwritten production were associated with activation in the left hemisphere cortical regions including SMA/superior frontal gyrus (BA 6), precentral gyrus/middle frontal gyrus/inferior frontal gyrus (BA 6/BA 44), superior/inferior parietal lobule/angular gyrus (BA 7/BA 39), and supramarginal gyrus (BA 40). Following earlier work (e.g., Yang et al., 2018), orthographic processing and the specific motor procedures for Chinese handwritten production were associated with bilateral hemisphere activation including the bilateral precentral gyri (BA 6), the left superior parietal lobule/superior frontal gyrus/postcentral gyrus (BA 7/BA 6/BA 4), the right inferior/superior parietal lobule (BA 40/BA 7), and the right putamen/thalamus. Our fMRI results also revealed no brain activation associated with the main effects of word frequency and syllable frequency as well as their interaction. Together, these results provide a full picture of the neural substrates of cognitive processes involved in Chinese handwritten production and also imply that word frequency and syllable frequency may not affect the writing of Chinese characters on a neural level. These results are discussed in more detail below.

### Handwritten Production-Specific Brain Regions in Chinese

#### *Frontal Cortex Activation*

In the frontal cortex, we identified a large amount of activation in the left hemisphere associated with Chinese handwritten production including the left superior/middle frontal gyrus (BA 6) and inferior frontal gyrus (BA 44). The activation in the left superior/middle frontal gyrus (BA 6) region was identified in both contrasts of “writing > watching plus drawing” and “writing > speaking plus drawing,” which suggests that this region may be associated with orthographic processing and/or the specific motor procedures necessary for Chinese handwritten production. Specifically, it has been suggested that left superior frontal gyrus/sulcus (BA 6) activation is associated with the graphemic buffer that is responsible for the temporary storage of graphemic representations before forming written motor commands (Cloutman et al., 2009; Beeson & Rapcsak, 2002). This interpretation is further supported by an fMRI study that reported that activation in the left

superior frontal sulcus (BA 6) was sensitive to the manipulation of word length processed in graphemic buffer during English spelling (Rapp & Dufor, 2011). To compare our results to this earlier work, we calculated the Euclidean distance between the peaks of the left superior frontal gyrus identified in our two contrasts (TAL peak =  $-19, -16, 65$  in “writing > watching plus drawing”; TAL peak =  $-21, -19, 64$  in “writing > speaking plus drawing”) and the peak of the left superior frontal sulcus (TAL peak =  $-13, -11, 51$ ) obtained in the Rapp and Dufor (2011) study. The results of this calculation showed distances of approximately 16 and 17 mm between the peaks of our superior frontal gyrus activation and that in the study by Rapp and Dufor (2011). It can therefore be inferred that the function of the left superior frontal gyrus identified in the present study is likely associated with the processes in orthographic/graphemic buffer common to both nonalphabetic (e.g., Chinese) and alphabetic (e.g., English) writing systems.

Another possibility regarding the function of the left superior/middle frontal gyrus (BA 6) region is that it plays an important role in the conversion of graphemic/orthographic representations to motor commands. Evidence for this comes from previous neuropsychological literature that has identified a writing-specific region (i.e., Exner’s area; Exner, 1881) that is localized in the left superior frontal gyrus and posterior middle frontal gyrus (BA 6), and this region is primarily involved in the translation of orthographic representations into various shapes and sizes of handwritten letters (i.e., allographic processing; Roux et al., 2009; Lubrano, Roux, & Démonet, 2004). However, the left superior/middle frontal gyrus (BA 6) region identified in our study is likely not to be the Exner’s area, as the peak of this region, especially the middle frontal gyrus (MNI peak =  $-54, 0, 45$ ), is not very close to the Exner’s area (MNI peak =  $-26, -8, 45$  for right-handed participants) identified in the Roux et al. (2009) study: The Euclidean distance is 30 mm. This finding suggests that the left superior/middle frontal gyrus region may not be closely related with the allographic processing in Chinese handwritten production.

Furthermore, the left middle frontal gyrus (MNI peak =  $-54, 0, 45$ ) identified in the contrast of “writing > watching plus drawing” is also very close to (9 mm) the phonological processing area (Rolandic sulcus; MNI peak =  $-47, -6, 44$ ) determined by a meta-analysis study on brain–language relationships (Vigneau et al., 2006). This finding suggests that left middle frontal gyrus activation may be responsible for phonological processing during Chinese writing. Combined, the left superior/middle frontal gyrus region could be associated with the processes involved in orthographic buffer and the phonological processing of Chinese handwritten production.

We also identified a significant activation in the left inferior frontal gyrus (BA 44) in the contrast of “writing > watching plus drawing,” which is consistent with previous studies (e.g., Yang et al., 2018, 2019; Chen et al., 2016),

supporting that left inferior frontal gyrus activation plays an important role in the writing of Chinese characters. Left inferior frontal gyrus activation could be associated with the processing in orthographic lexicon, as demonstrated by Rapp and Dufor (2011) who showed that activation in the left inferior frontal junction including the left inferior frontal gyrus was associated with orthographic knowledge for words with a low word frequency greater than those with a high word frequency. However, our results provide evidence against the association of the left inferior frontal gyrus region with the processes of orthographic lexicon in Chinese writing, as we did not detect any activation in this region associated with the word frequency effect.

A plausible function of the left inferior frontal gyrus region is that it is related to phonological processing during Chinese handwritten production. This is because previous literature (e.g., Fiez, Tranel, Seager-Frerichs, & Damasio, 2006; Poldrack et al., 1999; Fiez, 1997) has suggested that the left inferior frontal gyrus, especially the pars opercularis (BA 44), is associated with phonological processing involved in written language production. Consistent with this, Purcell, Napoliello, et al. (2011) have illustrated that the BA 44 region is related to unique phonological demands required for spelling including holding phonological representations temporarily in working memory before spelling. In addition, the left inferior frontal gyrus could also be associated with semantic processing of writing in Chinese, which is supported by the calculation that the peak of this region (MNI peak =  $-42, 6, 30$ ) obtained in our study has only a 6-mm Euclidean distance from the peak of the semantic processing area (precentral gyrus/F3op junction; MNI peak =  $-42, 4, 36$ ) of language processing identified in a meta-analysis study (Vigneau et al., 2006). Overall, then, we favor an interpretation that the left inferior frontal gyrus may be associated with the phonological and/or semantic processing involved in Chinese handwritten production.

In the “writing > speaking plus drawing” contrast, we found activation associated with writing in Chinese in the right frontal cortex, that is, the right precentral gyrus (BA 6). This matches observations from a meta-analysis by Planton et al. (2013) where peaks of the right frontal region (close to the precentral sulcus) were reported in various writing tasks. Our results are also consistent with Roux et al. (2009), who have proposed that this region is the right homologue of the left writing-specific prefrontal area (also referred as graphemic/motor frontal area), which serves an interface between graphemic abstract representations and the formation of motor command. This interpretation is further supported by Sugihara et al. (2006), who reported a significant left superior frontal peak in both left-hand and right-hand writing as well as a symmetrical, right-hemisphere peak when writing with only the left hand. Because bilateral precentral gyrus (BA 6) activation was identified in right-hand writing in our study, we infer that because of high visual-spatial complexity of Chinese characters, writing may require a

synchronized activity of the bilateral prefrontal areas that are responsible for the conversion of abstract orthographic representations to motor command.

### *Parietal Cortex Activation*

The activation map associated with Chinese handwritten production supports a long-standing claim that the left parietal cortex plays an important role in written production (Menon & Desmond, 2001; Alexander, Fischer, et al., 1992; Roeltgen & Heilman, 1985). Specifically, we identified activation in the left superior parietal lobule (BA 7), supramarginal gyrus (BA 40), and angular gyrus (BA 39). Left superior parietal lobule (BA 7) activation was identified in both contrasts of “writing > watching plus drawing” and “writing > speaking plus drawing,” which suggests that it is associated with the processes common to the two contrasts such as orthographic processing and/or specific motor procedure necessary for writing Chinese characters. Evidence from neuropsychological studies supports the latter interpretation, as lesions to the left superior parietal lobule lead to impairment of generating correct sequence of movements required for handwritten production (Sakurai et al., 2007; Alexander, Fischer, et al., 1992).

Another plausible interpretation is that left superior parietal lobule (BA 7) activation is associated with the orthographic buffer where orthographic representations are temporarily stored. This is supported by Rapp and Dufor (2011) who found that the left superior parietal lobule was sensitive to a manipulation of word length that was assumed as an indicator of orthographic buffer in spelling. Crucially, the left superior parietal lobule peak (TAL peak =  $-28, -50, 52$ ) reported in the Rapp and Dufor (2011) study has Euclidean distances of 13 mm and 7 mm from the peaks identified in our two contrasts (TAL peak =  $-27, -62, 47$  in “writing > watching plus drawing”; TAL peak =  $-27, -57, 52$  in “writing > speaking plus drawing”). On the basis of these findings, we suggest that the left superior parietal lobule may serve as the neural substrate of the generation of correct sequences of movements and/or the orthographic buffer required for Chinese handwritten production.

In the inferior parietal cortex, we identified left supramarginal gyrus (BA 40) and angular gyrus (BA 39) activation when comparing “writing” with “watching plus drawing.” Left supramarginal gyrus activation is consistent with previous studies that indicate that lesions to this region result in impaired written word production. Such a type of impairment leads to difficulties in pseudoword spelling but preserves relatively intact ability to spell both regular and irregular familiar words, which suggests that left supramarginal gyrus activation is associated with the processing of phoneme-grapheme conversion that pseudoword spelling relies on (Henry, Beeson, Stark, & Rapcsak, 2007; Philipose et al., 2007). This is further supported by neuroimaging studies that have found that left

supramarginal gyrus activation is related to phoneme–grapheme mapping required for spelling Japanese phonograms (Sugihara et al., 2006; Katanoda, Yoshikawa, & Sugishita, 2001). Therefore, writing in Chinese is associated with activation in the left supramarginal gyrus because of its inherent reliance on the conversion from phonology (i.e., Pinyin) to corresponding orthographic word forms.

Our finding of left angular gyrus (BA 39) activation suggests it could play a significant role in Chinese handwritten production. However, the specific function of the left angular gyrus with regard to written production is unclear. Several studies have suggested that the left angular gyrus is involved in the retrieval of orthography from the orthographic lexicon because lesion to this region results in difficulties in irregular word spelling (Roeltgen & Heilman, 1984; Beauvois & Dérouesné, 1981), whereas others have found that it is associated with the processing of sublexical phoneme–grapheme conversion in writing (Sheldon, Malcolm, & Barton, 2008; Hillis et al., 2002). Another possible functional role of the left angular gyrus is for conceptual/semantic processing in writing, as activation in the left angular gyrus has been reported in the tasks that require considerable concept/semantic processing such as narrative production as opposed to production of simple units (e.g., Seghier, Josse, Leff, & Price, 2011; Brownsett & Wise, 2010; Binder, Desai, Graves, & Conant, 2009). Overall, although the interpretations of the orthographic lexicon and phonology–orthography conversion cannot be ruled out, a strong case can be made for the role of the left angular gyrus region in some aspect of concept/semantic processing.

In addition to left parietal activation, we also identified activation in the right superior/inferior parietal lobule (BA 40/BA 7) when comparing “writing” with “speaking plus drawing.” This fits with results from a meta-analysis by Planton et al. (2013) where activation in the right inferior parietal lobule was reported during handwriting with various tasks or contrasts. Planton et al. (2013) proposed that right superior/inferior parietal lobule activation might be associated with the demands of visual–attentional control and visuomotor coordination, as these regions are primary nodes of the goal-directed attention network (e.g., Tunik, Ortigue, Adamovich, & Grafton, 2008; Corbetta & Shulman, 2002; Yantis et al., 2002; Nobre et al., 1997). However, this interpretation seems implausible for the activation in the right superior/inferior parietal lobule in our study because participants were asked to write their responses on the same position of the paper without visual monitoring, which means they did not need to direct their spatial–visual attention during handwriting.

We suggest an alternative possible cognitive role of the right superior/inferior parietal lobule: This region may support the complex orthographic processing required by writing Chinese characters. Compared to alphabetic languages that have a linear structure, writing Chinese characters relies on the retrieval of orthographic

representations with a more complex visual–spatial property from the orthographic lexicon and the temporary storage of these complex representations in orthographic buffer, which may require the activation in the right superior/inferior parietal lobule. Further research is therefore required to determine the specific functionality of this region in Chinese handwritten production.

Note that subcortical substrates in the right hemisphere, including the putamen and thalamus, were also identified when comparing “writing” with “speaking plus drawing,” which suggests that these substrates are involved in orthographic processing and/or specific motor commands required for writing Chinese characters. To our knowledge, activation in the right putamen is novel to our study, but activation in the right thalamus is known to be involved in the regulation of movements in left-hand writing (e.g., Planton et al., 2013; Sugihara et al., 2006). Right thalamus activation may reflect the involvement of a motor control pathway that receives cerebellar inputs and projects to the motor/premotor cortex (Middleton & Strick, 2000). Because we found right thalamus activation when writing with the right, rather than left, hand, it may imply that this region is associated with the additional motor control required for writing Chinese characters because of their square configuration. Further studies need to be carried out to explore the function of the right putamen and thalamus in Chinese handwritten production.

In addition, to link brain activation to behavioral performance, we correlated brain regions for the “writing” task with written latencies across participants and found that greater activation in the left Rolandic operculum (BA 41), the right paracentral lobule (BA 5), and the right lingual gyrus was associated with better written performance (i.e., shorter written latencies). Previous literature in other domains has shown that the left Rolandic operculum (BA 41) may play a role in sensory–motor adjustments or integration during speech articulation (see Vigneau et al., 2006). Activation in the paracentral lobule has been observed during unilateral complex finger movements (Roland, Meyer, Shibasaki, Yamamoto, & Thompson, 1982), and the right lingual gyrus is associated with global shape processing of words or objects (Fink et al., 1996). These findings imply that efficient handwritten production in Chinese may be associated with more activation in brain regions responsible for processing visual and motor information. The functional significance of activation correlated with handwritten performance should be explored further.

### **Brain Regions Associated with the Effects of Word Frequency and Syllable Frequency**

To examine the neural substrates crucial to the orthographic and phonological lexicons involved in Chinese handwritten production, we manipulated the word frequency (high, low) and syllable frequency (high, low) of

picture names. Behavioral results showed reliable effects of word frequency (43 msec) and syllable frequency (24 msec) but no interaction between the two factors, which is consistent with the finding by Zhang and Wang (2014). Contrary to the behavioral results, we did not find any brain activation associated with the main effects of word frequency and syllable frequency. We also did not observe any activation correlated with the interaction between the two factors. These results imply that word frequency and syllable frequency may affect writing performance only on a behavioral level. The inconsistency between the measurements of behavior and BOLD responses may be because the BOLD responses are less sensitive to the manipulations of word frequency and syllable frequency than the written latencies.

We did not identify any activation associated with the main effects of word frequency and syllable frequency in Chinese handwritten production, which is partially consistent with the observation by Chen et al. (2016) that no brain activation associated with the word frequency effect in a Chinese writing contrast (stroke judgment > form judgment) at a statistical threshold with cluster FDR < 0.05. The null effects may be because of minimized demands of recognizing a character by selecting among multiple word forms (see also Chen et al., 2016): None of the Chinese characters in the current study has homophones, which means each of them has their own unique orthographic and phonological word forms. The demand of retrieving a Chinese character by selecting the correct orthography and phonology among multiple candidates is minimized, which eliminates the effects of word frequency and syllable frequency on the BOLD responses. This interpretation is further supported by our finding that no activation associated with the main effects of word frequency and syllable frequency was identified in the “speaking plus drawing” task at a strict FDR-corrected threshold of  $p < .05$ .

Another plausible interpretation for the absence of the main effects of word frequency and syllable frequency on BOLD responses may be because of too few observations in each condition in our study, that is, 60 trials for the “writing” task in which there were only 15 trials for each condition. This may lead to null effects at an FDR-corrected threshold. The lack of activation associated with the main effects could also be because the repetition of picture stimuli (i.e., three repetitions, for the familiarization first, then for the behavioral test, and finally for the fMRI test) might elicit adaptation to the stimuli and then alleviate the brain activation associated with the effects of word frequency and syllable frequency. This possibility has been supported by a behavioral study showing that the effects of word frequency and syllable frequency were attenuated with the repetition of picture stimuli (Zhang & Wang, 2014). Thus, to avoid potential low statistical power, larger effects, more trials, and less repetition of the stimuli would be recommended for future neuroimaging studies.

We also did not find any activation associated with an interaction between word frequency and syllable frequency either on the written latencies or on the BOLD responses. This finding implies that phonological codes may not influence orthographic processing (or vice versa), which may support the orthographic autonomy hypothesis (Miceli et al., 1997; Rapp et al., 1997). However, one may argue that the absence of the interaction may be because of too few observations (15 trials per participant) in each condition, which leads to null activation at a strict FDR-corrected threshold ( $p < .05$ ). To test this possibility, we applied a relatively liberal uncorrected threshold of  $p < .005$  and reported only clusters with a minimum of 30 contiguous voxels. We found an interaction between word frequency and syllable frequency reflected on the BOLD responses, which was associated with the activation in the right precuneus/superior parietal lobule (BA 7) and right superior temporal gyrus (BA 13; see Appendix B: Table B1).

Specifically, the word frequency effect (low > high) in the low-syllable-frequency condition was associated with activation in the right superior temporal gyrus/insula (BA 13), with no such an effect in the high-syllable-frequency condition (see Table B2 and Figure B1). Because activation in the right superior temporal gyrus/insula has been reported in the tasks requiring considerable phonological processing (e.g., comparing the rime spelling of auditory words; see Booth et al., 2002, 2004), we infer that this region may be associated with the phonological processing when writing Chinese characters with a low syllable frequency. We also found that activation in the left inferior/superior parietal lobule (BA 40/BA 7) was associated with the syllable frequency effect (low > high) for pictures names with a low word frequency only (see Table B2 and Figure B1). This region (MNI peak =  $-39, -39, 51$ ) identified in our study only has a Euclidean distance of 7 mm from the left inferior parietal lobule activation (MNI peak =  $-32, -42, 51$ ) associated with phonological processing in Chinese observed in a meta-analysis (Wu, Ho, & Chen, 2012). Thus, the left inferior/superior parietal lobule region may be associated with the temporary storage of phonological information when writing Chinese characters with a low word frequency. These results suggest that the retrieval of orthography of Chinese characters may require the involvement of phonological processing, which may support the “phonological mediation hypothesis” (Luria, 1970; Geschwind, 1969). Note that this conclusion is not reliable because of the lenient statistical threshold ( $p < .005$ , uncorrected); more neuroimaging research is needed to reveal the relationship between phonology and orthography in writing.

### Limitations and Outlook

The present study found that handwritten production in Chinese was mainly involved in activation in the bilateral frontal and parietal cortex and that no activation associated

with the main effects of word frequency and syllable frequency as well as their interaction. These findings advance our understanding of the universal and specific principles guiding the organization of the Chinese writing system in the brain. However, the current study has the following limitations. First, the sample size (23 participants) is relatively small for our design in which the target “writing” task contains 60 observations in total and each condition (e.g., high word and syllable frequency condition) only has 15 trials, which may increase the likelihood of false-positive result and undermine the reliability of the findings (Eklund, Nichols, & Knutsson, 2016; Button et al., 2013). A larger sample size should be considered in future fMRI research.

Second, the present study did not match the trial number between the experimental tasks (60 trials for the “writing” task and “speaking plus drawing” tasks, respectively) and the baseline control task (20 trials for the “watching plus drawing” task). An uneven number of trials for different conditions may lead to an issue of heteroscedasticity, with a less-certain estimate for the condition with the fewest trials. This may undermine the statistical sensitivity and the reliability of the results. Future fMRI study, therefore, should take the same (or similar) number of trials for different conditions into account when designing the experiment.

Finally, similarly to previous studies (e.g., Planton, Longcamp, Péran, Démonet, & Jucla, 2017; Segal & Petrides, 2012; Rapp & Dufor, 2011; Katanoda et al., 2001), the present study did not provide participants with visual feedback during their handwriting, which is distinct from real-world writing context. There were two major

concerns for the handwriting without visual feedback: One was technical limitations, and the other was that the visual feedback may elicit additional brain activation associated with visuospatial processing (e.g., monitor the spatial layout of the paper sheet). However, a few recent studies provided their participants with written responses on a screen in real time via a mirror on the scanner’s head coil (e.g., Vinci-Booher & James, 2020a, 2020b; Vinci-Booher, Cheng, & James, 2019; Yang et al., 2019; Vinci-Booher, Sturgeon, James, & James, 2018), which implies that the technical limitation is no longer the main concern for the presentation of the visual feedback during writing. Thus, a better control task for the visuospatial processing could more precisely identify writing-specific visual monitoring processing in future studies.

## Conclusions

This study provides insights into the neural substrates supporting Chinese handwritten production. Writing Chinese characters was primarily associated with brain activation in the left frontal and parietal cortex, whereas orthographic processing and motor procedures necessary for handwritten production were also related to activation in the right frontal and parietal cortex as well as right putamen/thalamus. These results suggest that writing Chinese characters requires the involvement of brain activation in the bilateral cerebral hemispheres. The absence of activation associated with the effects of word frequency and syllable frequency implies that word frequency and syllable frequency may not affect Chinese handwritten production on a neural level.

## APPENDIX A: STIMULI USED IN THE PRESENT STUDY

**Table A1.** 60 Pictures Used in the Present Study

High word frequency	High syllable frequency	烟钟耳火鱼旗脚鸡房叶镜羊鞋星树
	Low syllable frequency	球床船桥佛炮狗枪腿兵桌浪轮窗虫
Low word frequency	High syllable frequency	斧弓盒桶梳笛梯豹虾鼠梨钳锯燕鲸
	Low syllable frequency	锚熊猫爪拐茄蛙锤琴巢耙鞍袜鹅龟

**Table A2.** Mean Values of Word Frequency (per Million), Syllable Frequency (per Million), and Six Other Psycholinguistic Variables of the Stimuli

	Word Frequency	Syllable Frequency	Number of Orthographic Neighbors	Number of Strokes	Name Agreement	Image Familiarity	Image Agreement	Image Complexity
<i>High word frequency</i>								
High syllable frequency	297	5898	9.27	9.13	1.06	4.80	3.76	2.42
Low syllable frequency	255	869	2.87	9.13	1.24	4.32	3.19	2.50
<i>Low word frequency</i>								
High syllable frequency	28	5253	8.40	10.87	1.05	4.29	3.46	2.34
Low syllable frequency	22	716	3.47	10.67	1.05	4.39	3.71	2.51

## APPENDIX B: RESULTS OF ACTIVATION ASSOCIATED WITH WORD FREQUENCY AND SYLLABLE FREQUENCY AT A RELATIVELY LIBERAL STATISTICAL THRESHOLD ( $P < .005$ , UNCORRECTED)

**Table B1.** List of Anatomical Regions, Volumes, Maximal Z Values, and Peak Coordinates for the Interaction between Word Frequency and Syllable Frequency

Anatomical Region (Estimated Brodmann's Area)	Volume (Voxels)	$Z_{max}$	MNI Coordinates			TAL Coordinates		
			$x$	$y$	$z$	$x$	$y$	$z$
<i>Main effect of word frequency (low &gt; high)</i>								
No significant clusters								
<i>Main effect of syllable frequency (low &gt; high)</i>								
No significant clusters								
<i>Interaction between word frequency and syllable frequency</i>								
Parietal lobe								
R precuneus	160	4.57	18	-42	48	15	-45	43
R precuneus		3.62	6	-57	57	4	-60	50
R superior parietal lobule (BA 7)		3.53	18	-54	63	15	-58	56
Temporal lobe								
R superior temporal gyrus (BA 13)	62	4.11	45	-39	18	40	-40	17

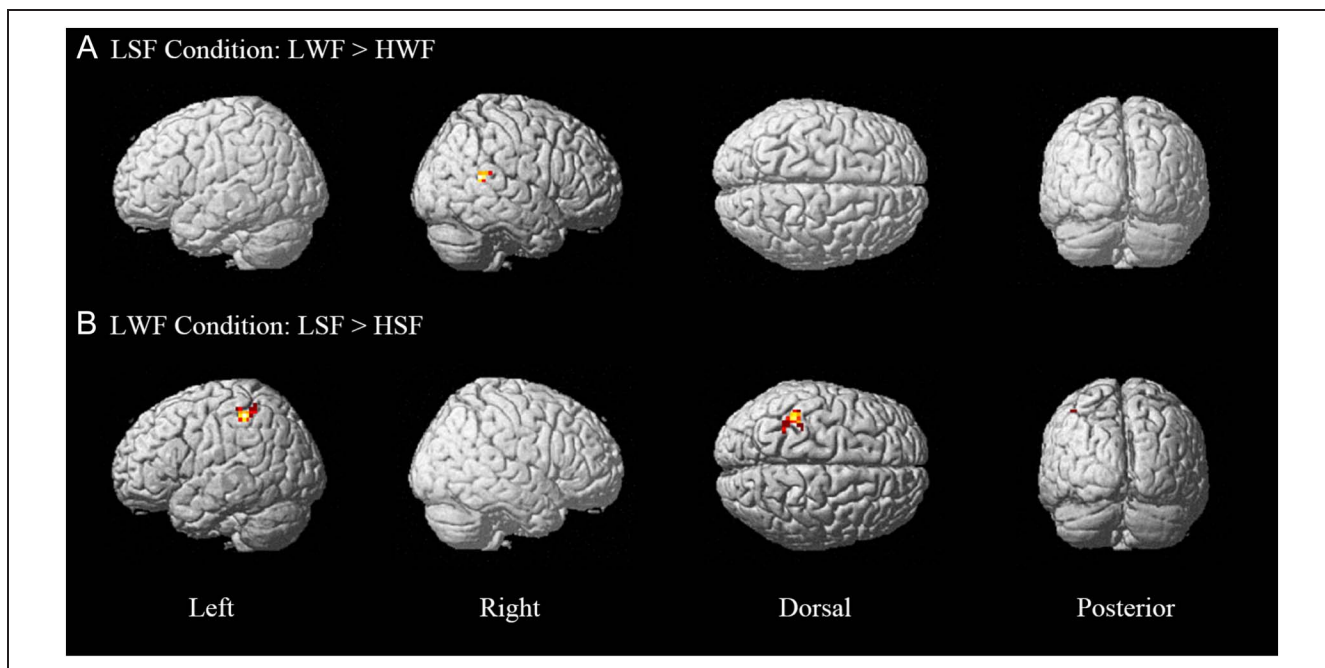
$n = 21$  ( $p < .005$ , uncorrected; cluster size = 30). R = right.



**Table B2.** List of Anatomical Regions, Volumes, Maximal Z Values, and Peak Coordinates for the Simple Effects of Word Frequency and Syllable Frequency

Anatomical Region (Estimated Brodmann's Area)	Volume (voxels)	$Z_{max}$	MNI Coordinates			TAL Coordinates		
			<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
<i>Word frequency effect (low &gt; high) in the low-syllable-frequency condition</i>								
Temporal lobe								
R superior temporal gyrus (BA 13)	33	3.78	48	-42	15	43	-42	15
R insula (BA 13)		3.42	42	-39	21	38	-40	20
<i>Word frequency effect (low &gt; high) in the high-syllable-frequency condition</i>								
No significant clusters								
<i>Syllable frequency effect (low &gt; high) in the low-word-frequency condition</i>								
Parietal lobe								
L inferior parietal lobule (BA 40)	50	4.08	-39	-39	51	-38	-42	46
L superior parietal lobule (BA 7)		2.84	-30	-48	57	-30	-51	50
L inferior parietal lobule (BA 40)		2.64	-30	-33	60	-30	-38	54
<i>Syllable frequency effect (low &gt; high) in the high-word-frequency condition</i>								
No significant clusters								

$n = 21$  ( $p < .005$ , uncorrected; cluster size = 30). L = left; R = right.



**Figure B1.** Whole-brain contrast maps for the simple effects of word frequency (low > high) and syllable frequency (low > high). Each was projected on a standard rendered SPM template brain. Only clusters surpassing 30 voxels are shown. LWF and HWF refer to low word frequency and high word frequency, respectively; LSF and HSF refer to low syllable frequency and high syllable frequency, respectively. (A) Map of clusters for the LWF > HWF contrast in the low-syllable-frequency condition ( $p < .005$ , uncorrected). (B) Map of clusters for the LSF > HSF contrast in the low-word-frequency condition ( $p < .005$ , uncorrected).

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## Data Availability Statement

All stimuli and data that support the findings of this study are openly available in OSF at [osf.io/t3kh7/](https://osf.io/t3kh7/).

## Author Contributions

Jieying He: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing—Original draft; Writing—Review & editing. Laurel Brehm: Writing—Review & editing. Qingfang Zhang: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Writing—Review & editing.

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## Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were  $M(\text{an})/M = .407$ ,  $W(\text{oman})/M = .32$ ,  $M/W = .115$ , and  $W/W = .159$ , the comparable proportions for the articles that these authorship teams cited were  $M/M = .549$ ,  $W/M = .257$ ,  $M/W = .109$ , and  $W/W = .085$  (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows:  $M/M = .509$ ,  $W/M = .226$ ,  $M/W = .151$ , and  $W/W = .113$ .

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