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Brain activation and functional connectivity during Chinese writing: An fMRI study

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ABSTRACT

How the brain processes writing in Chinese is largely unknown. Using functional magnetic resonance imaging (fMRI) with kinematic recording, this study examined the brain activation and functional connectivity associated with writing to dictation of Chinese characters, contrasted with drawing circles, in 33 healthy adults. It was found that writing Chinese characters recruited activation in the bilateral precentral gyrus, superior/medial frontal gyrus, fusiform gyrus, cerebellum and the left precuneus that were associated with the central and peripheral processes of writing. Functional connectivity related to Chinese writing was observed between the left precuneus and both the left pre/postcentral gyrus and the bilateral cerebellum that likely supports motor processing, whereas functional connectivity observed between the right fusiform gyrus and both the bilateral inferior/middle occipital gyrus and the right middle frontal gyrus likely supports orthographic processing. Moreover, the functional connectivity between the left inferior frontal gyrus and left superior frontal gyrus reflected the interaction between linguistic and motor processes, supporting the interactive hypothesis concerning the relationship between central and peripheral processes of writing. These findings illustrate the neural mechanisms of Chinese writing, extending our knowledge of the cognitive processing required for this form of human communication.

1. Introduction

Writing, specifically handwriting, is an important form of human communication that requires the synchronization of cognitive, linguistic and perceptual-motor operations. From a cognitive perspective, writing behavior is thought to be broadly supported by two

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distinct components: a central processing component for retrieving appropriate words and correct orthographic form via orthographic long-term memory or phoneme-to-grapheme conversion; and a peripheral processing component for retrieval of written form via allographic/letter-shape conversion and for guiding of specific motor programs (Ellis, 1982). There are two major hypotheses regarding the relationship between the central and peripheral components of writing. The first hypothesis posits that the central and peripheral processes are dissociable (Baxter & Warrington, 1986; Planton, Jucla, Roux, & Démonet, 2013; J. Purcell, Turkeltaub, Eden, & Rapp, 2011). According to this hypothesis, orthographic processing is complete before the initiation of motor processing. The other hypothesis argues that the central and peripheral processes are interactive (Kandel & Perret, 2015; S.; Roux, Mckeeff, Grosjacques, Afonso, & Kandel, 2013; Zhang & Feng, 2017). From this point of view, the central processing cascades onto the peripheral processing.

Over the past several decades, researchers have made considerable progress in determining the precise details of how these components of writing are implemented at the neural level. Present knowledge of the neuroanatomy of writing originate primarily from studies of individuals with writing impairments. Pure agraphia, a selective impairment of writing skill in the absence of other cognitive-linguistic and motor deficits, often presents as a lesion in the posterior part of the left middle frontal gyrus (Exner's area) (Anderson, Damasio, & Damasio, 1990; Exner, 1881; F. E.; Roux et al., 2009) and the left intraparietal sulcus/superior parietal lobule (Alexander, Fischer, & Friedman, 1992; Sakurai et al., 2007). Lesions in the posterior middle and inferior temporal gyrus (fusiform gyrus) (Rapcsak & Beeson, 2004) lead to the lexical agraphia that is characterized by difficulty in writing to dictation of irregular words, while writing ability for regular words and nonwords is preserved, suggesting the left inferior temporal cortex including the mid-fusiform gyrus is important for orthographic recall during writing (Rapp & Dufor, 2011; Rapp & Lipka, 2011).

Consistent with these lesion studies, noninvasive measurements of brain activity using functional magnetic resonance imaging (fMRI) have demonstrated the brain regions involved in various writing behaviors, including writing to dictation (Nakamura et al., 2002; Omura, Tsukamoto, Kotani, Ohgami, & Yoshikawa, 2004; Planton, Longcamp, Péran, Démonet, & Jucla, 2017), written naming (Katanoda, Yoshikawa, & Sugishita, 2001; Sugihara, Kaminaga, & Sugishita, 2006) and generative writing of words (Beeson et al., 2003). Specifically, by using a written picture naming task in Japanese kana and two control tasks (silent naming of pictures and finger tapping), Katanoda et al. (2001) reported that the left posterior part of the middle and superior frontal gyrus, the left superior parietal lobule and the right cerebellum were commonly activated in the comparisons of writing versus the two control conditions. Furthermore, the left middle/superior frontal gyrus and the superior parietal lobule were found to be commonly activated in writing with right and left hand in written naming of pictures in kana (Sugihara et al., 2006), implying that these regions were specific to writing processing. Furthermore, several fMRI studies have attempted to differentiate the brain regions activated for central and peripheral processes respectively by employing different control tasks (Beeson et al., 2003; Nakamura et al., 2000; Roux et al., 2009). For instance, by contrasting the generative writing of single words to writing letters of the alphabet in a written naming task, the brain activation related to orthographic forms of words was found to involve the left posterior inferior temporal lobe and the left inferior and dorsolateral prefrontal cortex (Beeson et al., 2003). Likewise, an fMRI study reported that transcription of kana to kanji Japanese characters and subsequent mental recall yielded left-lateralized activation in the left posterior inferior temporal cortex that was not observed in semantic judgment tasks and reading tasks (Nakamura et al., 2000), supporting the role of the posterior inferior temporal gyrus in orthographic processing in writing. By contrasting writing the alphabet to drawing circles, the brain activation related to specific peripheral processing (graphomotor programming and the motor execution of writing) was identified, involving the superior parietal lobule, the inferior and middle frontal gyrus and the primary motor areas (Beeson et al., 2003). Using fMRI in a writing-to-dictation task, a commonly used task paradigm (Omura et al., 2004; Rapp & Dufor, 2011; Roux et al., 2009), the left premotor area extending to Broca's area was identified as the neural substrate for the phoneme-to-grapheme conversion in writing, by contrasting the brain activation of writing Japanese phonograms to that of writing meaningless symbols (Omura et al., 2004).

In summary, previous lesion and neuroimaging studies have revealed widely distributed neural networks related to writing including the frontal motor cortex, the superior parietal lobule, the inferior temporal gyrus (fusiform gyrus) and the cerebellum (Planton et al., 2013; J. J. Purcell, Turkeltaub, Eden, & Rapp, 2011). However, the exact roles of these regions in writing remains inconclusive. Generally, the posterior middle frontal gyrus (Exner's) is implicated as the region that provides the link between orthography and motor programs specific to writing (F. E. Roux et al., 2009), while the intraparietal lobule/superior parietal lobule and the cerebellum are believed to support the sensorimotor control for writing (Harrington, Farias, Davis, & Buonocore, 2007; Planton et al., 2013; Planton et al., 2017). Finally, the left inferior temporal cortex including the mid-fusiform gyrus is the neural substrate of orthographic retrieval in writing (Nakamura et al., 2000; Planton et al., 2013; Purcell et al., 2011).

A major challenge to investigate the neural substrates of writing is the ecological validity of the writing task. Previous neuroimaging studies of writing have used both “imagined” (Harrington et al., 2007) and “actual” writing tasks (Beeson et al., 2003; Nakamura et al., 2002; Rapp & Dufor, 2011). In imagined writing, the roles of sensorimotor and visual feedback are not incorporated realistically during writing performance, as participants are required to perform implicitly by imagined movement and mental imagery, while remaining still. Beyond the difficulty in establishing task compliance in imagined movements, visual feedback is a very important factor that mediates writing performance by providing an online inspector to modify writing gestures and speed (Danna & Velay, 2015). Other studies used actual writing tasks requiring participants to write on paper or digital tablet (Beeson et al., 2003; Nakamura et al., 2002; Rapp & Dufor, 2011). The behavioral recordings of writing were often not compared with well-designed control conditions, such that low-level kinematic processing was not closely matched. This matching is important to account for variations in the duration of letter writing time, which potentially can modulate blood oxygenation level-dependent (BOLD) fMRI signals in the motor-perceptual network (Longcamp et al., 2014). Thus, to approach a ‘real’ neural network of writing, an actual writing task with online kinematic recording during fMRI scanning is necessary. This setup poses practical challenges, but with the development of MRI-compatible digital writing tablet technology (Tam, Churchill, Strother, & Graham, 2011), these challenges have been resolved to some extent. Recently, a few fMRI studies have used such devices to demonstrate the neural network specific to writing processing after regressing out the variance related to low-level kinematic activity in more realistic writing contexts (Karimpoor et al., 2018; Longcamp et al., 2014; Planton et al., 2017).

On the other hand, despite this progress in localization of the discrete regions necessary for writing, there has been little investigation of how writing-related brain regions are functionally integrated together. To our knowledge, only one fMRI study has examined the functional connectivity underlying writing, using a written naming task to show that the left inferior parietal sulcus/superior parietal lobule was connected with the language regions (Segal & Petrides, 2012). Thus, more research of functional connectivity is needed to expand the map of the neural network associated with writing. Moreover, functional connectivity analysis would also be beneficial for exploring the relationship between the central and peripheral processes.

Also in need of more research are differences in brain activity and functional integration across different languages and writing systems. Chinese differs dramatically from alphabetic languages. The basic unit of written Chinese is the character, a combination of radicals that are formed by strokes. Unlike the linear structure of alphabetic words, which are constructed by sequences of letters, Chinese characters have a square configuration, yielding a high level of visual complexity. In addition to the script-level features, the relationship between orthographic, phonological and semantic systems is complex because Chinese includes a large number of homophones with a single syllable shared by many characters. Evidence from neuroimaging studies of Chinese reading has demonstrated that the neural substrates of reading in Chinese are significantly distinct from those of alphabetic languages (Ge et al., 2015; Siok, Niu, Jin, Perfetti, & Tan, 2008; Siok, Perfetti, Jin, & Tan, 2004). Do the complex features of written Chinese yield a characteristic signature of brain activity associated with writing? A lesion study found a double dissociation of writing impairments between Japanese kanji (the adopted logographic Chinese characters used in Japanese) and kana (a syllabic writing system used in Japanese), suggesting that the associated neural pathways are different (Sakurai, Matsumura, Iwatsubo, & Momose, 1997). Very few fMRI studies have addressed this question directly, with inconsistent results (Cao & Perfetti, 2016; Cao et al., 2013; Chen, Chang, Chen, Lin, & Wu, 2016; Lin, Xiao, Shen, Zhang, & Weng, 2007; Nakamura et al., 2012). Using an imagined writing task in a group of native Chinese speakers, an event-related fMRI study (Lin et al., 2007) investigated the brain activation associated with writing Chinese characters and pinyin (the romanization system for standard Chinese in mainland China). The results indicated that writing both types of symbols recruited the same brain networks with varying activation extent in the left middle frontal gyrus, superior parietal lobule, posterior inferior temporal gyrus and cerebellum. However, the direct comparison between characters and pinyin did not reveal any brain regions that were more activated for Chinese characters, and thus this study did not reveal brain regions specific to Chinese writing. Similarly, another fMRI study reported that Chinese and French readers showed similar activation in the occipitotemporal visual word-form area and the left premotor region (Exner's area) when reading words written in cursive font (Nakamura et al., 2012). Evidence for a language difference was observed by Cao and Perfetti (2016) using an imagined writing task. Directly comparing the brain activation when writing Chinese characters versus English words, they found that Chinese elicited greater activation in the middle frontal gyrus than English, both in English-speaking learners of Chinese and native Chinese speakers. The left middle frontal gyrus was thought to serve the orthography-motor connection in Chinese writing (Cao & Perfetti, 2016). In line with this hypothesis, another recent fMRI study examined the orthographic buffer supporting Chinese writing by manipulating the number of strokes of Chinese characters in an imagined writing task in which participants were required to mentally write Chinese characters and to retain the last stroke to be compared with the probe. It was found that the activation of the left middle frontal gyrus was sensitive to the number of strokes, suggesting that it is involved in storage of orthographic information in Chinese writing (Chen et al., 2016). These latter studies support the argument that the neural substrates of writing might vary across language systems.

However, the imagined writing tasks that were used in these previous neuroimaging studies of Chinese writing (Cao & Perfetti, 2016; Chen et al., 2016) have limitations that may have biased the end results and their interpretation. As mentioned above, the low-level motor processing was not controlled, possibly leading to confounding brain activation in the motor cortex related to the execution and control of hand movements. Furthermore, the imagined writing tasks fail to incorporate the roles of sensorimotor and visual feedback, thus straying far from the processes engaged in everyday handwriting and their neural basis.

The present study aimed to investigate brain activation and functional connectivity associated with Chinese writing in an actual writing context. An fMRI-compatible computerized tablet was used to enable realistic writing behavior and to record kinematic responses during neuroimaging such that low-level motor control of hand movements were well matched between writing and control conditions, for improved exploration of writing-specific brain mechanisms. Furthermore, this writing tablet enabled participants to see the written outputs in real time to better approximate an “actual” writing circumstance as much as possible. We hypothesized that more complete brain networks would be identified for the actual writing of Chinese characters compared with previous fMRI studies using imagined writing tasks (Cao & Perfetti, 2016; Chen et al., 2016; Lin et al., 2007), including the brain regions known to be associated with central and peripheral components of writing: the superior and middle frontal gyrus, the superior/inferior parietal lobule, the inferior temporal gyrus (fusiform gyrus) and the cerebellum (Planton et al., 2013; Purcell et al., 2011). Additionally, we also expected to observe unique brain activation associated with Chinese writing. Due to the square configuration and complex visual properties, writing a Chinese character requires a high level of visual-spatial processing. We expected to observe distinctive brain activation in the right occipital gyrus that has been linked to visual analysis of Chinese characters (Cao et al., 2009; Tan et al., 2001). Frequent changes of focus on different locations within the square character space might also result in many attentional shifts. Significant activation in the posterior parietal lobule (e.g. precuneus) was anticipated as it has been found to support attentional shifts in motor processing (Wenderoth, Debaere, Sunaert, & Swinnen, 2005). Beyond task related activation, we expected to observe the functional integration within the visual orthographic network (Xu, Wang, Chen, Fox, & Tan, 2015), the frontal-parietal motor network (Schulz et al., 2015) and the cerebellar motor network (Stoodley & Schmahmann, 2010) for central and peripheral components of writing respectively. In addition, since several behavioral studies have suggested that central and peripheral processes interact during written production (Roux et al., 2013; Zhang & Feng, 2017), cross-modal functional connectivity between linguistic and motor regions was anticipated.

2. Materials and methods

2.1. Participants

Thirty-three adults were recruited to participate in this study (18 males and 15 females; mean age = 22.55 years, range from 19 to 28). All the participants were native Chinese speakers and were right-handed as assessed by a handedness inventory (Snyder & Harris, 1993). The participants were physically healthy and had no history of neurological disease or psychiatric disorder. The study was approved by the ethics committee of the Institute of Psychology, Chinese Academy of Sciences, and the methods were carried out in accordance with the approved guidelines. Prior to the experiment, written informed consent was obtained from each participant.

2.2. Stimuli and task procedure

A writing-to-dictation task was used in which participants were required to write the first characters of two-character Chinese words given in auditory presentation. To control for activation elicited by motor and auditory processing, participants also performed a task in which they were asked to ignore the sounds of words while drawing circles. The motor processing of circle drawing shares a lot with that of writing, while not being tightly associated with language; thus, its face validity as a control for motor activation is good. In addition, circle drawing has proven useful as a control task in multiple previous fMRI studies of writing (Beeson et al., 2003; Rapp & Dufor, 2011; Roux et al., 2009). To match the motor processing, participants were instructed to begin each trial when the cue appeared (a yellow pencil symbol), and then to match the duration and size while writing characters or drawing circles, stopping when the response slide disappeared. Participants were instructed to write or draw on an fMRI-compatible tablet in their normal writing style while minimizing the movements of their upper arm and forearm. The tablet included a touch-sensitive surface, a force-sensitive stylus and an adjustable support frame, and it enabled recording of response times (RTs) as well as writing and drawing results (Tam et al., 2011). The written responses on the tablet were recorded and displayed on a screen in real time, and participants had an unobstructed view of this feedback via a mirror on the scanner's head coil. The RTs of writing characters and drawing circles were defined as the duration from the start of the response period to the end of the last written or drawn stroke of the response. The support frame was adjusted carefully for each participant to ensure that writing and drawing could be undertaken comfortably throughout the imaging session, and to enable tablet interaction with the forearm or wrist resting on the support such that there was no fatigue from writing against gravity in a supine position. Thus, the experimental setup was designed to simulate as closely as possible a naturalistic writing situation within the fMRI environment, with the exception that visual feedback was shown in the mirror with no hands obstructing the line of sight, similar to how one uses a commercial graphics tablet on the desktop. Prior to the fMRI session, participants underwent a practice session to familiarize them with the tasks and with writing or drawing on the tablet without seeing their hands.

A block design was employed, consisting of three blocks of writing characters and three blocks of drawing circles in pseudo-random order. Each block included visual presentation of instructions for 2 s followed by five trials. In each trial, a '+' symbol was first presented visually and centrally for 0.3 s, followed by presentation of auditory stimuli for 1 s and then a response period of 4.7 s (Fig. 1A). Four blocks of central fixation, each with 12 s duration, were also interspersed among the task and control blocks as a “rest” condition. The total time for this design was 240 s.

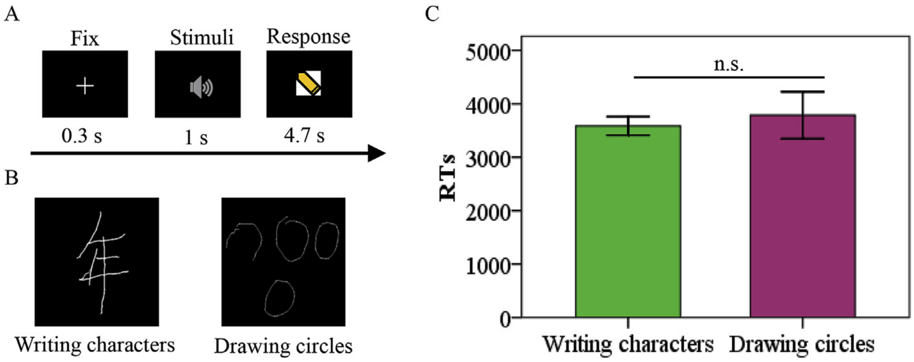

Fig. 1. Experimental design and behavioral recordings during fMRI. (A) Temporal structure of each writing and drawing task trial. (B) Example behavioral performance of writing characters and drawing circles for a representative participant. (C) Descriptive and statistical analysis of RTs for writing characters and drawing circles across the group of participants. Error bars denote the standard error of the mean. n.s. = not significant.

2.3. Imaging acquisition

MRI data were continuously collected on a Siemens Prisma^{fit} 3T MRI scanner at the Beijing MRI Center for Brain Research of the Chinese Academy of Sciences. Functional MRI time series data were acquired using a BOLD-sensitive T2*- weighted gradient-echo echo planar imaging (EPI) sequence (Moeller et al., 2010) (repetition time TR = 1000 ms, echo time TE = 30 ms, slice thickness = 2.2 mm, in-plane resolution = 2.2 mm × 2.2 mm and flip angle = 45°). Sixty-four axial slices were collected. High spatial resolution anatomical images were acquired using a T1-weighted, magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence (TR = 2200 ms, TE = 2.08 ms, slice thickness = 1.0 mm, in-plane resolution = 1.0 mm × 1.0 mm and flip angle = 8°).

2.4. Data analysis

2.4.1. Preprocessing

Image preprocessing and statistical analyses were conducted using SPM8 (http://www.fil.ion.ucl.ac.uk/spm/, Wellcome Department of Cognitive Neurology, University College London, London). The fMRI time series data for each participant were first corrected for head motion, and the realigned images were coregistered to the high-resolution T1 anatomical imaging data. The anatomical images were normalized into Montreal Neurological Institute (MNI) stereotactic space, and the resulting warp parameters were applied to yield fMRI time series data that were normalized in MNI space with cubic voxels at 2 mm × 2 mm × 2 mm spatial resolution. The normalized functional images were then smoothed with an 8-mm full-width at half-maximum isotropic Gaussian kernel. Three participants were excluded from the following analysis due to excessive head motion ($>$ 2 mm translation or $>$ 2° rotation). Another participant was excluded due to signal loss in the prefrontal cortex.

2.4.2. Brain activation analysis

Activation maps contrasting writing characters to drawing circles were generated for each participant by the general linear model (GLM) method. The GLM design matrix included the block design time series convolved with a canonical hemodynamic response function. To minimize residual motion artifacts, head movement parameters (estimated with six degrees of freedom during the motion correction step mentioned above) were included in the design matrix as nuisance covariates. The data were high-pass-filtered at 128s (0.008 Hz). Group analyses for brain activation were subsequently performed with a random-effects model using a one-sample *t*-test. The voxelwise threshold for statistically significant activation was set at $p < 0.01$, false discovery rate (FDR) corrected for multiple comparisons with a minimum cluster extent of 20 contiguous voxels. Brain regions were estimated from the Talairach atlas (Talairach & Tournoux, 1988).

2.4.3. Functional connectivity analysis

To examine context-dependent functional integration, a seed-to-voxel functional connectivity analysis was also performed using the CONN-fMRI toolbox for SPM8 (Whitfield-Gabrieli and Nieto-Castanon, 2012). Seeds were functionally defined based on the brain activation of Chinese writing identified by this study, which were constrained within the well-known brain regions related to writing (Planton et al., 2013; Purcell et al., 2011), including the left superior frontal gyrus ($x = -6$, $y = 9$, $z = 57$, in Talaraich coordinates), the bilateral precentral gyrus (left: $x = -42$, $y = -6$, $z = 39$; right: $x = 53$, $y = 0$, $z = 44$), the left precuneus ($x = -20$, $y = -58$, $z = 49$), the bilateral fusiform gyrus (left: $x = -42$, $y = -57$, $z = -9$; right: $x = 38$, $y = -43$, $z = -13$) and the right cerebellum ($x = 0$, $y = -62$, $z = -27$). Spherical regions of interest (ROIs) were created centered on each of these coordinate locations with a radius of 8 mm. Nuisance BOLD signal fluctuations were reduced by using linear regression to remove signals from cerebrospinal fluid and white matter regions, motion parameters and their derivatives. The task design convolved with a hemodynamic response function was also regressed out, and the resulting data were high-pass filtered at 0.008 Hz. Bivariate correlation coefficients were then computed to assess correlation of the fMRI time series signal from these seed ROIs to the rest of the voxels in the brain, with transformation to Fisher's Z-scores. Maps contrasting functional connectivity during writing characters blocks to rest and to drawing circles blocks were generated for each participant, and then were put into a random effects group analysis using a one-sample *t*-test. Significant correlations were reported that survived a voxel-wise threshold of $p < 0.001$, uncorrected and a cluster-level threshold of $p < 0.05$, FDR corrected. To further elucidate the nature of the functional connectivity, we extracted for inspection the coefficients of functional connectivity that showed statistically significant differences between task and control conditions.

3. Results

3.1. Behavioral results

Because four participants were excluded due to image artifacts (from excessive head motion and signal loss), behavioral performance was reportable from twenty-nine participants. Example behavioral performance of the task and control condition is shown in Fig. 1B for a representative participant. Overall, participants were able to complete the task and control conditions well, and the mean accuracy of writing characters was 0.91 (standard deviation (SD) = 0.08). The mean RTs of writing characters and drawing circles were 3582 ms (SD = 455 ms) and 3785 ms (SD = 1160 ms), respectively (Fig. 1C). Importantly, paired *t*-test results indicated no statistically significant differences in RT between writing characters and drawing circles [$t(28) = -0.86$, $p = 0.395$].

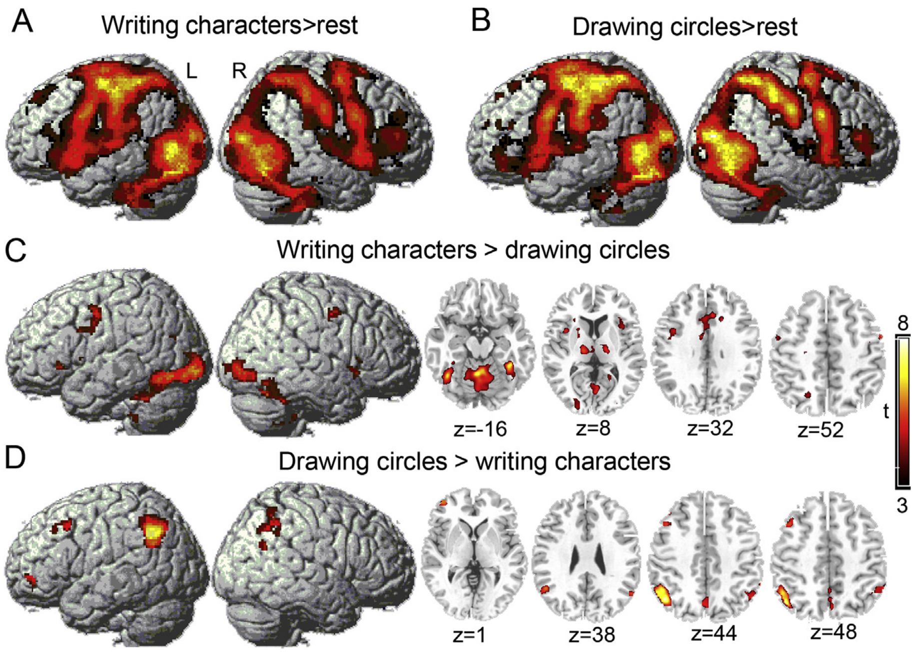

Fig. 2. Brain regions with significant activation during actual Chinese writing and drawing circles. (A) Activation for the contrast writing characters minus rest; (B) Activation for the contrast drawing circles minus rest; (C) Activation for the contrast writing characters minus drawing circles; (D) Activation for the contrast drawing circles minus writing characters. L = left and R = right.

3.2. fMRI results

3.2.1. Activation analysis

When contrasted with the rest condition, writing characters and drawing circles each elicited a similar, widespread activation pattern with major contributions from the sensorimotor and language regions (Fig. 2 A & B). When writing characters and drawing circles were subsequently contrasted, the differences were observed much more sparsely in the brain. The writing characters minus drawing circles contrast yielded significant activations in the bilateral precentral gyrus (BA4/6), the left superior frontal gyrus (BA6), the bilateral inferior frontal gyrus (BA9/45/47), the bilateral insula (BA13), the left superior parietal lobule (BA7), the bilateral fusiform gyrus (BA37) and the cerebellum (Table 1, Fig. 2C). In addition, the drawing circles minus writing characters contrast yielded significant activations in the left precentral gyrus (BA9), the left middle frontal gyrus (BA10), the left inferior parietal lobule (BA40), the right precuneus (BA7) and the left angular gyrus (BA39) (Table 1, Fig. 2D).

3.2.2. Functional connectivity analysis

We found that writing characters and drawing circles recruited large-scale interregional interactions within the superior/middle frontal gyrus, superior parietal lobule, fusiform gyrus, occipital gyrus and cerebellum. We focused on the functional connectivity specific to Chinese writing via the contrast between writing characters and drawing circles. Specifically, compared to drawing circles, writing characters resulted in greater functional connectivity between the left precuneus and both the left precentral/postcentral gyrus ($r = 0.12$, $p < 0.001$) and the bilateral cerebellum (left declive: $r = 0.11$, $p < 0.001$; right culmen/declive: $r = 0.1$, $p < 0.001$), as shown in Fig. 3A. In analogous fashion (Fig. 3B), writing characters also resulted in increased functional connectivity between the right fusiform gyrus and the left inferior/middle occipital gyrus ($r = 0.1$, $p < 0.001$), the right lingual gyrus ($r = 0.11$, $p < 0.001$), the right middle frontal gyrus ($r = 0.1$, $p < 0.001$) and the left postcentral gyrus ($r = 0.11$, $p < 0.001$), in relation to the functional connectivity observed for drawing circles. Finally, writing characters resulted in increased functional connectivity between the left superior frontal gyrus and the left inferior frontal gyrus ($r = 0.11$, $p < 0.001$) relative to drawing circles (Fig. 3C).

4. Discussion

The present study investigated the neural underpinnings of actual Chinese writing by comparing the activity and functional connectivity between writing Chinese characters from auditory dictation and drawing circles. In line with our hypotheses, the results revealed both similarities and dissimilarities in brain activation related to writing between Chinese and alphabetic languages. Consistent with previous findings in other languages (Planton et al., 2013; Purcell et al., 2011), numerous brain regions were found to be engaged in actual Chinese writing—including the bilateral frontal motor regions, the left superior parietal lobule (precuneus), the left fusiform gyrus and cerebellum—as required to support the central and peripheral components of neural processing that underlie writing behavior. We also found brain activation in the right fusiform gyrus and the right middle occipital gyrus in Chinese writing,

Table 1

Coordinates of activation peaks for contrasts between writing characters and drawing circles. Z-score corresponds to the actual maximum pixel value within the brain region from the statistical parametric map. L = left and R = right, BA= Brodmann's area.

Brain regions	BA	Talairach			z score
		x	y	z	
Writing characters > drawing circles					
Frontal					
L precentral gyrus	6	−42	−6	39	4.54
	4	−26	−21	42	3.97
	4	−28	−15	43	3.62
R precentral gyrus	6	53	0	44	4.88
L superior frontal gyrus	6	−6	9	57	3.99
L Inferior frontal gyrus	9	−40	7	27	4.13
	47	−38	25	−3	3.57
R inferior frontal gyrus	47	20	23	−11	4.11
	45	34	25	4	3.54
L insula	13	−38	8	7	4.38
R insula	13	30	−9	23	4.09
Temporal					
L middle Temporal gyrus	39	−30	−65	24	3.87
	19	−32	−61	21	3.81
L fusiform gyrus	37	−42	−57	−9	5.52
R fusiform gyrus	37	38	−43	−13	5.38
Parietal					
L precuneus	7	−20	−58	49	3.89
Occipital					
L inferior occipital gyrus	19	−38	−82	−6	5.42
L middle occipital gyrus	18	−34	−87	−1	4.77
R inferior occipital gyrus	19	44	−78	−3	4.69
R middle occipital gyrus	18	36	−86	−1	4.51
L cuneus	17	−22	−95	0	4.43
R cuneus	17	22	−95	1	3.57
	30	2	−69	9	4.35
Subcortical areas					
L cingulate gyrus	24	−8	−1	28	4.59
R anterior cingulate	32	18	21	25	4.61
R posterior cingulate	30	20	−50	10	3.85
L caudate		10	18	16	4.1
L putamen		−22	10	7	3.94
R putamen		20	8	14	4.01
L claustrum		−26	21	3	3.97
R claustrum		36	14	3	3.94
L thalamus		−14	−17	8	4.55
R thalamus		18	−9	13	4.91
Cerebellar					
L culmen		−38	−42	−20	4.78
L declive		−18	−57	−16	4.58
L tonsil		−22	−43	−37	3.78
R uvula		0	−62	−27	5.67
R culmen		2	−53	−16	5.54
R declive		0	−63	−15	5.05
R tonsil		30	−56	−39	4
Drawing circles > writing characters					
Frontal					
L precentral gyrus	9	−42	19	40	4.64
L middle frontal gyrus	10	−44	50	−4	5.27
	11	−46	46	−12	4.14
Temporal					
L superior temporal gyrus	39	53	−59	29	4.52
Parietal					
L inferior parietal lobule	40	−46	−60	45	5.72
R precuneus	7	0	−66	44	4.31
R inferior parietal lobule	40	57	−44	45	4.37
L angular gyrus	39	−44	−58	38	5.89

which might reflect the unique brain mechanisms of Chinese writing due to the visual features of Chinese characters (Cao et al., 2009; Tan et al., 2001). Moreover, based on a seed-to-voxel functional connectivity analysis, the present study revealed how these regions specifically interact during Chinese writing. The identified regional activation and functional connectivity were independent of low-level kinematic processes, due to well-controlled experimental conditions and direct evidence of comparable reaction times for

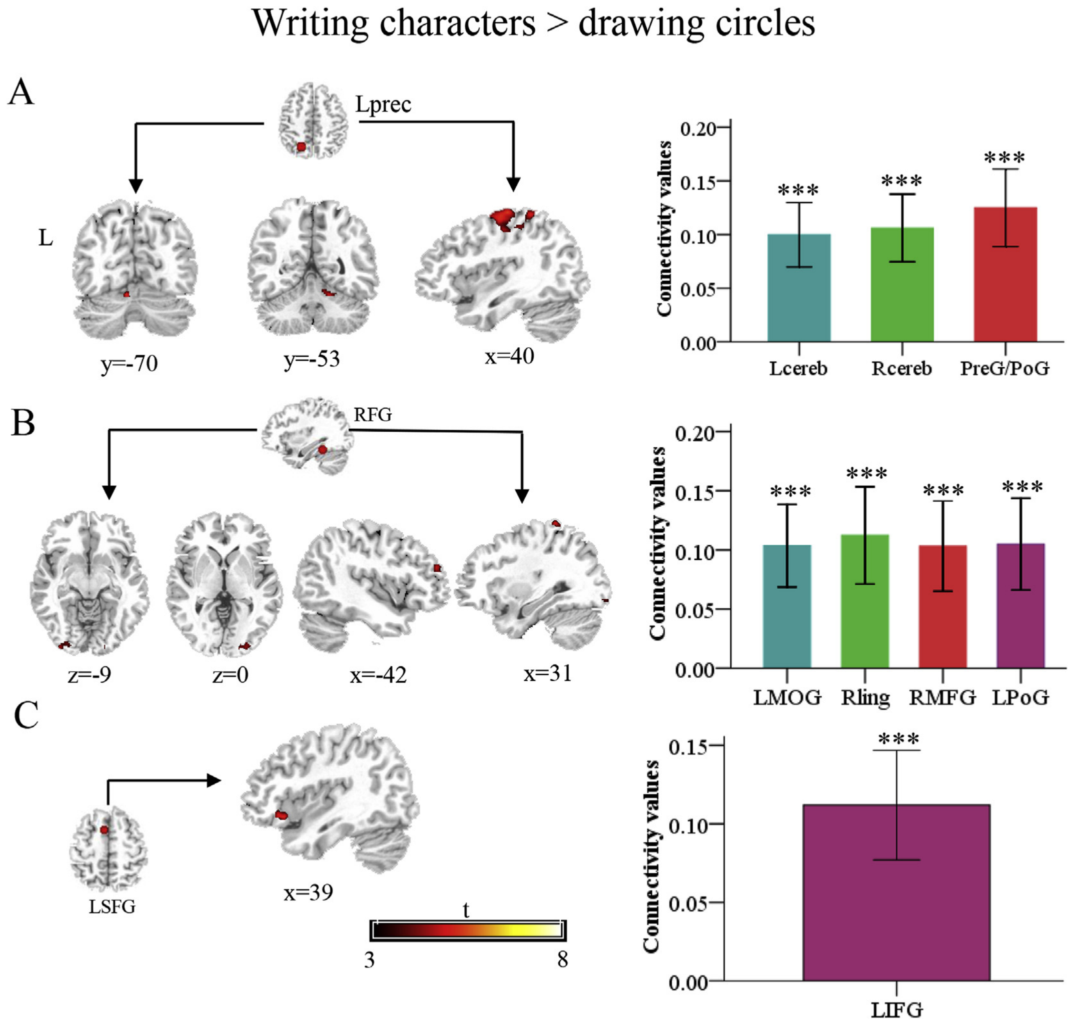

Fig. 3. Functional connectivity associated with writing characters. (A) Brain regions showing positive connectivity with the left precuneus seed and the corresponding connectivity coefficients. (B) Brain regions showing positive connectivity with the right fusiform gyrus seed and the corresponding connectivity coefficients. (C) Brain regions showing positive connectivity with the left superior frontal gyrus seed and the corresponding connectivity coefficients. Prec = precuneus, Cereb = cerebellum, PreG = precentral gyrus, PoG = postcentral gyrus, MOG = middle occipital gyrus, ling = lingual gyrus, FG = fusiform gyrus, SFG = superior frontal gyrus, MFG = middle frontal gyrus, IFG = inferior frontal gyrus. L = left and R = right. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

writing characters and drawing circles. We found that, the extent of brain activation identified by the actual writing task was more focal than that revealed by the imagined writing tasks (Cao & Perfetti, 2016), although the activated brain regions were relatively overlapping. Thus, the current findings were more likely to represent the specific brain substrates of Chinese writing. Furthermore, the applicability of the results was strengthened by the use of a novel fMRI-compatible tablet system that enables measurement of brain activity during writing and drawing behavior with higher realism than previous studies. A detailed discussion follows.

4.1. Brain regions related to actual Chinese writing

4.1.1. The frontal region

Brain activation was observed in the left precentral gyrus (BA4/6) (peak: -42 -6 39 in Talairach coordinates) during actual Chinese writing, close to the coordinates for Exner's area (-46 -4 43) (Matsuo et al., 2003). Previous neuroimaging studies have repeatedly reported activation of Exner's area across different task paradigms in alphabetic languages (Beeson et al., 2003; Harrington et al., 2007; Longcamp et al., 2014; Planton et al., 2013; Roux et al., 2009; Sugihara et al., 2006) and Chinese (Cao & Perfetti, 2016; Lin et al., 2007), albeit with subtle differences in the peaks of activation. Furthermore, Cao and Perfetti (2016) reported that the left posterior middle frontal gyrus (−50 2 26), which neighbors the peak of activation in the precentral gyrus found in the present study, was more involved in Chinese writing than English. This region was thought to support the motor programming in memory for writing (allographic processing), the peripheral component of writing (Purcell et al., 2011; Roux et al., 2009). Alternatively, Rapp and Dufor (2011) found that the activity in the precentral gyrus/superior frontal gyrus (-13 -11 51, BA6) was sensitive to the word length during writing production, and thus proposed that this region was the neural substrate of orthographic working memory. Likewise, a recent study in Chinese also showed that the activation in the posterior part of the left middle frontal gyrus (BA6) was modulated by the number of strokes of Chinese characters (Chen et al., 2016), favoring the notion that the left precentral gyrus might be responsible for the long-term retention of orthographic representation. Consequently, the activation in the left precentral gyrus might be associated with retrieval of orthographic forms of Chinese characters.

Another activation peak was located in the left superior frontal gyrus (−6 9 57), designated as within the supplementary motor area (SMA). Among its multiple roles, the SMA has been implicated in sequential motor processing (Nachev, Kennard, & Husain, 2008). Writing Chinese inherently involves serial motor processing that engages the activation of internal representations and the execution of motor sequences of writing units (e.g. strokes) as required to form a character. Thus, the left superior frontal gyrus (SMA) may have performed this role in the present experimental context.

4.1.2. *Superior parietal lobule*

Another main finding of the present study was the significant activation of the left superior parietal lobule (precuneus) during actual Chinese writing. Convergent evidence from lesion and neuroimaging studies has indicated that the superior parietal lobule is crucial to writing across language systems (Cao & Perfetti, 2016; Menon & Desmond, 2001; Otsuki, Soma, Arai, Otsuka, & Tsuji, 1999; Planton et al., 2013; Sugihara et al., 2006). Rapp and Dufor (2011) found that the superior parietal lobule was activated in an actual writing task, but not in a spelling task (Rapp & Lipka, 2011), implying its motor role in writing (Otsuki et al., 1999; Planton et al., 2017). Functionally, the superior parietal lobule was suggested to house the kinesthetic and sequential motor engrams of letters that support serial production of letter shapes during writing (Planton et al., 2013; Sakurai et al., 2007). An alternative viewpoint is that the superior parietal lobule acts as an interface that coordinates language and motor regions depending on the context of writing (Segal & Petrides, 2012). The specific role of the superior parietal lobule in Chinese writing needs further investigation, and cannot be elucidated from the present study design. However, one other notable observation was that the activation peak of the parietal lobule was located at (-20 -58 49) which seemed to be more posterior than that consistently reported in alphabetic languages (-32 -34 53) (Planton et al., 2013). One possibility for such discrepancy is that activation in this region can show high inter-individual variability. Sugihara et al. (2006) found that the activation peaks in the superior parietal lobule were more widespread than activation in other areas during writing, based on single-participant analysis. Another possibility is that Chinese writing has a high demand for visuospatial attention processing, due to the square configuration of the characters. The precuneus has been implicated in the process of shifting attention between different locations in space during movement execution (Wenderoth et al., 2005), as is particularly necessary for writing Chinese characters.

4.1.3. *Cerebellum*

The bilateral cerebellum was significantly activated during writing of Chinese characters. Cerebellar activation has been reported in generative writing (writing on the lap with pencil and paper with eyes closed during fMRI, contrasted with drawing circles in the same manner) (Beeson et al., 2003) and written naming (writing single grapheme kana characters in the air with the index finger, contrasted with oral naming) (Sugihara et al., 2006). In addition, a meta-analysis study identified two clusters in the right cerebellum that were activated during various writing tasks after controlling for motor output and linguistic input, confirming the specific role of cerebellum in writing (Planton et al., 2013). The cerebellum is a multifunctional structure that is involved in motor, cognitive and affective processes via its connectivity with cortical regions (Stoodley & Schmahmann, 2010). Specifically, motor tasks are more likely to activate the anterior cerebellum, whereas high-order cognitive tasks (language, working memory) are more likely to activate the posterior cerebellum (Stoodley & Schmahmann, 2009). Thus, the bilateral activation of the anterior cerebellum in the present study may reflect complex motor processing during Chinese writing. Alternatively, however, such activation may also reflect sequence processing for writing characters. Previous studies have shown that the cerebellum has a role in detection and production of sequences in both motor and cognitive domains (Bohland & Guenther, 2006; Gomez-Beldarrain, Garcia-Monco, Rubio, & Pascual-Leone, 1998; Penhune & Steele, 2012). Left cerebellar lesions were found to impair sequence processing of pictorial material, whereas right lesions impaired sequence processing requiring verbal elaboration (Leggio et al., 2008). Chinese writing requires both language-related and script-related functions of the cerebellum due to the high level of visual complexity of characters; thus the observation of bilateral cerebellar activation is not surprising.

4.1.4. *Fusiform gyrus*

Actual Chinese writing yielded activation in the bilateral fusiform gyrus. The left inferior temporal gyrus/fusiform gyrus has been found to be associated with retrieval of orthographic representation from long-term memory during writing processing (Matsuo et al., 2000; Nakamura et al., 2002; Rapp & Dufor, 2011; Rapp & Lipka, 2011). Furthermore, Nakamura et al. (2002) found that actual writing (with the index finger on a plastic board, without visual feedback) and mental recall of both kanji (ideogram) and kana (phonogram) by native Japanese speakers activated the left posterior inferior temporal cortex, suggesting that this region contributes to visual graphic processing for writing across different writing systems. However, activation of this region should not be thought of as writing-specific. Previous studies have demonstrated significant activation in the left fusiform gyrus in reading tasks in alphabetic languages (Dehaene et al., 2010; Philipose et al., 2007) and in Chinese (Tan, Laird, Li, & Fox, 2005; Wu, Ho, & Chen, 2012), although its specific role in reading is debatable (Price & Devlin, 2003).

In the present work, the right fusiform gyrus was significantly activated during Chinese writing-a rare observation in studies of alphabetic languages (Planton et al., 2013; Purcell et al., 2011). Right-sided activation of the fusiform gyrus has also been observed in several other studies of Chinese writing (Cao & Perfetti, 2016; Chen et al., 2016) and reading (Tan, Laird, et al., 2005). Functionally, the right fusiform gyrus is thought to be responsible for the organization of radicals into a characters (Liu & Perfetti, 2003) or the global processing of characters (Nelson, Liu, Fiez, & Perfetti, 2009) that is uniquely essential to Chinese language processing. Indeed, the Chinese character has multiple levels of visual representation (i.e. stroke, logographeme, radical, character), and the basic unit of writing in Chinese is a matter of debate (Han, Zhang, Shu, & Bi, 2007; Law & Leung, 2000). How the fusiform gyrus contributes to graphic processing of Chinese writing remains to be further examined, particularly with respect to the functional topography of both hemispheres.

4.2. Functional connectivity related to actual Chinese writing

4.2.1. Motor networks

Functional connectivity analyses further characterized the neural mechanisms of actual Chinese writing from the perspective of functional integration between writing-related regions. First, the present study found that writing characters increased the functional connectivity between the left superior parietal lobule (precuneus) and the left precentral gyrus. The corresponding cortical connections between the precuneus and the dorsal premotor area have been identified in non-human primate (Leichnetz, 2001) and humans (Hagmann et al., 2008). It has been suggested that the left precuneus serves the serial production of the shapes of letters, and that the precentral gyrus is involved in translation of the graphic engram into motor coding for writing (Cao & Perfetti, 2016), as governed by this fronto-parietal loop. In addition, increased functional connectivity was observed between the left precuneus and the bilateral anterior cerebellum. Anatomical and physiological studies have indicated that the parietal lobule is interconnected with cerebellum (Habas & Cabanis, 2007; Schmahmann & Pandya, 1989). As the anterior lobe of cerebellum is thought to be more involved in sensory-motor tasks (Stoodley & Schmahmann, 2009), the present cerebellar-parietal connectivity is ascribed to the motor control function for Chinese writing. In contrast to a prior study in alphabetic language that reported the functional connectivity between the superior parietal lobule and language-related regions (e.g. the left angular gyrus, the supramarginal gyus), the present study revealed the functional connectivity between the superior parietal lobule and motor regions. It is reasonable to speculate that the latter finding may result from the features of Chinese. Chinese writing may depend heavily on the orthographic route for writing processing because of the tight relation between the graphic representation and the associated motor program required to form characters, as developed through extensive practice and repetition (Tan, Spinks, Eden, Perfetti, & Siok, 2005).

Finally, functional connectivity was observed between the left precuneus and the left postcentral gyrus. Activation of the left postcentral gyrus has been repeatedly reported during written naming (Katanoda et al., 2001) and writing to dictation (Menon & Desmond, 2001), but its specific role in writing has been rarely discussed. One suggestion is that the left postcentral gyrus is engaged as part of the somatosensory feedback that is important during writing (Sakurai et al., 2007). For example, writing pressure is known to vary throughout a specific handwriting task, typically increasing progressively towards a maximum shortly before task completion (Kao, 1983). Consequently, the left postcentral-precuneus connectivity that was observed may indicate the importance of this effect when writing actual Chinese characters.

4.2.2. Orthographic networks

During writing, we found increased functional connectivity between the fusiform gyrus and the bilateral occipitotemporal cortex (covering the left lingual gyrus and the right middle occipital gyrus), suggesting the neural pathway for retrieving the orthographic form during Chinese writing. During visual word processing, activation of the bilateral temporo-occipital regions has been found to be greater for Chinese than for English due to the visual complexity of Chinese characters, and the increased demands on orthographic identification (Cao & Perfetti, 2016; Tan, Laird, et al., 2005). Consequently, the functional connectivity observed between the mid-fusiform gyrus and the bilateral posterior inferior occipital gyrus may be related to orthographic processing, and specifically the retrieval of the orthographic form of characters.

Additionally, Chinese writing recruited the functional connectivity between the right fusiform gyrus and the right middle frontal gyrus. The right middle frontal gyrus has been proposed as an important locus of attention networks that activate when individuals show reorienting behavior to unexpected stimuli (Shulman et al., 2009). Accordingly, the functional connectivity between the right middle frontal gyrus and the right fusiform gyrus could be considered as a mechanism of attentional monitoring for orthographic errors during writing. In the writing task that was implemented in the present work, participants were able to view their written responses simultaneously with their tablet interactions, and thus the visual information enabled feedback to monitor writing processing with higher realism than previous efforts (Burton, Pick, Holmes, & Teulings, 1990; Graham & Weintraub, 1996). Further studies are needed to investigate how the visual feedback aids writing processing.

4.2.3. Language-motor interaction

Significantly increased functional connectivity was observed between the left superior frontal gyrus (SMA) and the anterior left inferior frontal gyrus during writing. The left inferior frontal gyrus is a well-known language region that has been associated with phonological and semantic processing in Chinese (Wu et al., 2012). The functional connectivity between the frontal motor region and this language region is straightforwardly interpreted, therefore, as the constraint of writing performance by language processing. This notion is consistent with behavioral observations that show how writing processing is influenced by language factors including phonology (Zhang & Damian, 2010) or word frequency (Zhang & Wang, 2014). Thus, the functional connectivity between language and motor-related regions offers neural evidence for the interactive view of the relationship between central and peripheral processes during writing (Kandel & Perret, 2015; Roux et al., 2013), and it challenges the serial processing model of writing (Van Galen, 1991).

4.3. Limitations

The present study and its outcomes must be evaluated while considering three different limitations. First, this study only characterizes the neural mechanisms underlying the whole procedure of writing, because the experiment was not designed specifically to distinguish the central and peripheral components of writing and their respective neural activation signatures. Additional studies, possibly using additional control tasks or manipulation of the central and peripheral components respectively, are required in the future to disentangle the specific neural mechanisms of language and motor processing associated with actual Chinese writing behavior.

Second, non-directional functional connectivity analysis was used in the present study. Although important elevations in connectivity were shown between multiple brain regions, these initial findings are inconclusive regarding information flow. Directed connectivity studies and analyses will be needed to address this issue, for example to explore the underlying mechanisms of visual and somatosensory feedback during actual Chinese writing.

Finally, despite use of an fMRI-compatible tablet to record motor responses, and a novel control task that enabled RTs for writing characters and drawing circles to be matched at the group level, there is still some uncertainty over the influence of low-level manual motor activity on the present results. For instance, the low-level motor trajectory of drawing circles is different from that of writing characters. It is also possible some of the frontal and parietal activation seen in the control task could be linked to a difference in attentional allocation between conditions, perhaps in anticipation of the more interesting writing task, rather than language or motor processing. Future studies would benefit from examination of more kinematic variables, such as writing pressure and the time interval between various writing events, for better control and interpretation of motor factors involved in writing-specific neural mechanisms.

5. Conclusion

This study is the first to reveal the neural correlates of actual Chinese writing by investigating both brain activation and functional connectivity. Similarities and differences were identified in the brain activation associated with writing in Chinese in relation to writing in alphabetic languages. Furthermore, functional connectivity illustrated the neural synchronization within and between the cognitive, linguistic and perceptual-motor networks that underlie actual Chinese writing. These findings extend knowledge of the neural basis of writing, shed new light on cognitive models of writing, and lay the groundwork for future studies in this research field.

Author contributions

Y.Y., F.T., S.J.G., R.T., and H.Y.B. conceived and designed the experiment. Y.Y., Z.T.Z. and N.Z.W. performed the experiment. Y.Y., N.Z.W. and R.T. performed the data analyses. Y.Y., Z.T.Z and H.Y.B co-wrote the paper. Y.Y., Z.T.Z, F.T., S.J.G., N.Z.W., R.T., and H.Y.B. discussed the data and commented on the manuscript.

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