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# The Visual Word Form Area: Evidence from an fMRI study of implicit processing of Chinese characters

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**A notable controversy in neurolinguistics is whether there is a particular brain area specialized for visual word recognition within the visual ventral stream. We investigated this question via implicit processing of Chinese characters. Implicit processing of four types of stimuli – real characters, pseudo characters, artificial characters, and checkerboard – in two different sizes, were compared in 14 normal participants using functional MRI (fMRI) with a size judgment task. The results showed that when the three character types were contrasted to one another, there was significantly greater activation in the left middle fusiform gyrus during real and pseudo character processing compared to artificial characters. Moreover, individual analysis revealed that the coordinates were consistent with the Visual Word Form Area (VWFA) reported for alphabetic scripts. Results also showed a consistent activation in the left middle frontal gyrus (BA 9) for real and pseudo characters. The relation between this region and the VWFA in Characters processing still needs further investigation.**
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*Keywords:* fMRI; Implicit processing; Visual Word Form Area; Orthographic processing; Chinese character

## Introduction

Identification of a word form is the first step necessary for word recognition and reading. Warrington and Shallice (1980) first established that the visual identification of a word is achieved by an abstract representation in the brain, which they named the Visual Word Form (VWF). Recently, researchers focusing on the recognition of alphabetic scripts (Cohen et al., 2000, 2002, 2003; Dehaene et al., 2002, 2001; McCandliss et al., 2003) proposed that the middle fusiform gyrus of the left hemisphere is responsible for the processing of visual word forms and for the orthographic processing that constrains letter combinations during reading. This area was thus named the “Visual Word Form Area” (VWFA). Some of these researchers further proposed that this area should be reproducibly observed in all cultures, even in writing systems of nonalphabetic scripts (Cohen and Dehaene, 2004; McCandliss et al., 2003).

The question whether the VWFA can be identified in other writing systems other than alphabetic scripts, such as logographic scripts like Chinese characters, is still unclear. As the most widely used logographic script, Chinese characters have thousands of diverse word forms and differ markedly from alphabetic scripts in orthography. In Chinese characters, there is a distinctive square-combined configuration within each character and no obvious letter-sound correspondence (Chen, 1992; Chen and Juola, 1982). Although some phonological information is encoded in some characters, this information is not consistent and is not at a level of correspondences between phonemes and letters (Perfetti et al., 2005). In alphabetic stimuli, it is clear that each individual letter is the basic unit of words, so how different letters are combined is critical in defining orthographic regularities. In Chinese, however, it is still not clear what the basic processing units really are. Unlike the linear arrangement of alphabetical letters, more than 39% of Chinese characters are compound characters in the sense that they are formed by a phonetic part and a radical part representing a range of possible pronunciations and categories of meanings, respectively (Zhou, 1978). The phonetic and radical parts can be further divided into strokes or stroke patterns that constitute various components of characters. As a result, reading in Chinese

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*Abbreviations:* VWF, visual word form; VWFA, Visual Word Form Area; fMRI, functional MRI; TE, echo time; TR, relaxation time; SPM, statistical parametric mapping.

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requires much more complicated orthographic processing than in alphabetic scripts. These orthographic complexities make Chinese characters a good medium for investigating the VWFA problem.

Specifically, do Chinese characters activate the same location in the left middle fusiform gyrus as alphabetic scripts? Existing research has found that the left middle fusiform was activated by different experimental paradigms for Chinese, including semantic association, lexical decision, and character reading.(Chee et al., 2000; Chen et al., 2002; Kuo et al., 2004; Siok et al., 2004; Tan et al., 2001b, 2000). However, these studies did not produce a clear and consistent picture. For example, Siok et al. (2004) reported different activation of the left fusiform gyrus between the contrast of real and pseudo characters in a lexical decision task, whereas they found no difference when contrasting homophone judgments with font size judgments. In contrast, Kuo et al. (2004) obtained the opposite results, finding significant activations of the left occipital–temporal junction in homophone judgments vs. form judgments but no activation between contrasts of real and pseudo characters in form judgments. Thus, it is still not clear which components of language processing lead to the activation of the left middle fusiform area in processing Chinese characters. One of the difficulties in interpreting these differences in results lies in the fact that different tasks were used across the different studies, e.g., passive viewing, reading, naming, lexical judgments, homophone judgments, and categorizing. In addition, despite this variety of tasks, almost all of the tasks involved some form of explicit “reading,” which by default requires phonological or semantic access of the words, as well as extensive top-down processing that will activate a wide range of brain networks (Cohen and Dehaene, 2004). Thus, it is not clear that these previous studies could equally distinguish the visual processing of word form as an exclusive entity.

One way to deal with these task limitations is to engage an implicit task. It is now well known that linguistic processing can be highly automatic and implicit, and studies have reported that the mere presence of words automatically drives language-related brain areas even when the participants are not required to explicitly “read” the words, such as in a nonlinguistic feature detection task (Brunswick et al., 1999; Price et al., 1996; Turkeltaub et al., 2003) or a subliminal masking priming task (Dehaene et al., 2004b, 2001; Devlin et al., 2004). These implicit tasks, relative to their explicit counterparts, produce less phonological and semantic processing (Dehaene et al., 2001; Price et al., 1996); in addition, they also reduce the influence of attention and top-down analysis in explicit tasks that will recruit unnecessary processes (Booth et al., 2003, 2002; Cohen and Dehaene, 2004). These two advantages of implicit tasks could considerably minimize the influence of semantic and phonological processing, relative to explicit tasks, in investigating the VWFA problem.

Although many neuroimaging studies have been performed to identify neural activity related to explicit orthographic, phonological, and semantic processing of Chinese or other orthographic scripts, only a few have investigated the implicit processing of them. So far, we only found two studies of Japanese Kanji and Kana that have conducted implicit tasks, but both of them failed to identify the left middle fusiform gyrus as the VWFA. Thuy et al. (2004) found that the only left-lateralized activation in the occipital–temporal region for the Kanji/Kana vs. scrambled-character contrast was the posterior inferior temporal cortex. In another recent study using a masked priming task (Nakamura et al., 2005), the region specified for cross-script priming of Kanji and Kana was found to be associated with the left inferior temporal cortex anterior and dorsal to the VWFA. However, these two Japanese studies did not aim to identify the VWFA and Japanese is a hybrid writing system with both phonograms (Kana) and morphograms (Kanji), so the question is still quite open and an intensive examination of implicit processing of Chinese characters will be crucial for reexamining the VWFA problem in logographic scripts.

The main aim of our current study is to determine whether we can find evidence for a localized VWFA in the implicit processing of Chinese characters. Combining the materials used by Cohen et al. (2002) and Tagamets et al. (2000), we selected four kinds of stimuli in the current study: Real characters, Pseudo Characters, Artificial Characters, and Checkerboard (Fig. 1). Real characters are semantically meaningful, pronounceable, and orthographically

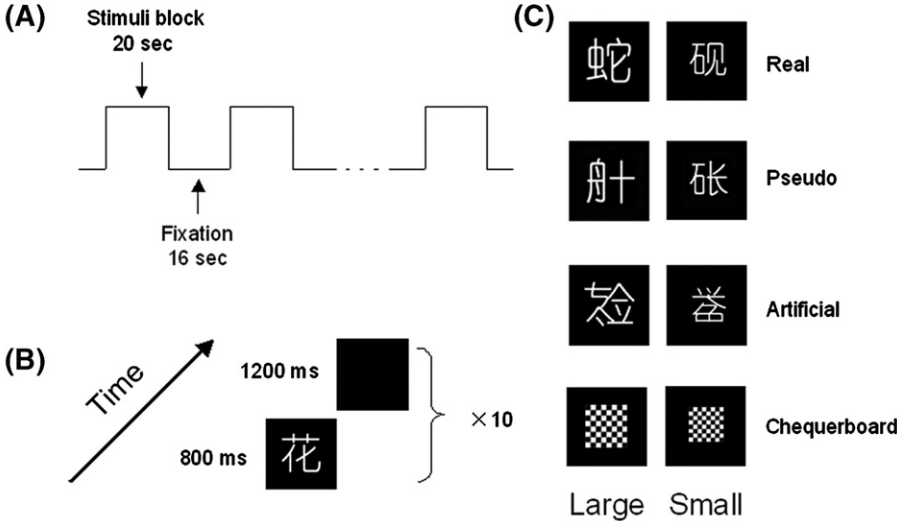

Fig. 1. (A) Each of the four types of stimuli was presented eight times with a Latin square design sequence, 32 stimuli blocks in total. (B) Each stimuli block contains 10 stimuli (five in large size, five in small size), presented in random order. (C) Four types of stimuli in large and small sizes.

legal. Pseudo characters are neither pronounceable nor meaningful at the holistic level, but follow orthographic rules. Artificial characters are meaningless and unpronounceable character components with no orthographic regularities. One important aspect in our design is the role of Pseudo characters. In previous studies with alphabetic scripts, pseudo words were both pronounceable and orthographically legal, so it was hard to dissociate orthographic processing from phonological processing. However, in our study, since the Pseudo Chinese characters are not pronounceable but are orthographically legal (imagine a consonant string, such as “nfsxr”, that is unpronounceable but contains legal “orthographic” information in English[1]), they can provide information relevant to pure orthographic processing when contrasted with Artificial characters that are visually similar but orthographically illegal (similar to the use of scrambled letter pieces in English). Thus, the contrast of Pseudo vs. Artificial characters in Chinese can offer us more precise information about orthographic processing than previous studies with alphabetic scripts. In order to further minimize extraneous processing demands, we used an implicit size judgment task (Siok et al., 2004; Tan et al., 2003; Thuy et al., 2004), which is frequently used as a control for phonological and semantic processing studies since its activation is believed to be due to the visual-orthographic processing of the linguistic stimuli (Price et al., 1997; Siok et al., 2004; Tan et al., 2003).

In the present study, we will focus on contrasts between orthographically legal Real and/or Pseudo characters and orthographically illegal Artificial characters. We are particularly interest in the Pseudo vs. Artificial contrast because, as mentioned above, only this particular contrast allows us to distinguish between characters that contain both visual and orthographic information (Pseudo characters) vs. those that contain visual components but no orthographic regularities (Artificial characters). Importantly, unlike English or other alphabetic scripts, neither of these character types are pronounceable nor have specific meaning associated with them. To examine these contrasts, we will first compare the four experimental stimuli to the fixation stimulus, then compare the three types of characters to the Checkerboard and, finally, focus our analysis on the comparisons within the three types of characters, with a focus on the Pseudo vs. Artificial contrast.

## Method

### *Participants*

Fourteen native Chinese-speaking university students (seven males), all aged 19–22 years, fully right-handed and with normal vision were paid for their participation in this study. All were drug free, had no neurological or psychiatric history, with normal anatomical MRIs.

### *Materials*

Eighty Chinese characters (nouns, YouYuan font) that have both high frequency (no less than 100 per million) and 7–14 strokes were used as Real characters. In Chinese, a word can consist of one or several characters. To control for this, the Real characters we used here were all single character nouns. Pseudo and Artificial characters were both created from Real character components. Pseudo characters were made by exchanging the sublexical components of Real characters we used. Their organization was based on two principles: (a) the components were exactly the same as those in our real characters, and (b) the components appeared in the correct position, which insured that the resulting pseudo characters were meaningless and unpronounceable at the holistic level but still orthographically legal (Siok et al., 2004). Artificial characters were made by reforming and/or reorganizing the unreadable sublexical components of Real characters. Both components and positions of Artificial characters were randomized to ensure that Artificial characters only retained visual aspects of Chinese characters without any other orthographic, phonological, or semantic information. Checkerboards having the same size as the characters served as a control.

All the stimuli were divided into two sizes: the Large size was 44pt and subtended approximately 3.6°of visual angle in a projector; the Small size was 36pt and subtended approximately 3°of visual angle. A centrally located crosshair subtended approximately 1° of visual angle and served as the fixation stimulus (Fig. 1).

### *Task*

The participants' task was to judge the size of stimuli as “large” or “small” by pressing two separated keys of a response box with their left or right thumb. Response hands were counterbalanced across participants. For the baseline condition, participants kept still and fixated at the fixation stimulus without any response.

### *Procedure*

A block design procedure was used such that each of the four types of stimuli was presented for eight blocks in a Latin square design sequence, with 32 stimulus blocks in total. The sequence consisted of 10 s of initial fixation, followed by 32 stimuli blocks of 20 s each (with a 16 s fixation interval between two blocks), then ended with a 10 s final fixation. Each 20 s stimulus block consisted of 10 stimuli of a single type (5 large, 5 small, presented in random order) that were each presented for 800 ms followed by a 1200 ms interval (Fig. 1). In total, there were 80 presentations of each stimulus type.

### *Image acquisition*

Images were acquired from a Siemens 3T scanner (TR = 2000 ms, TE = 30 ms, 25 axial slices with 4-mm-thick each, field of view 220 × 220 mm, acquisition matrix was 64 × 64, flip angle 90°, in-plane resolution = $3.4 \times 3.4$ mm$^2$). Eighty time points were acquired in each condition. High-resolution T1-weighted images were obtained for each subject to provide detailed anatomy ($1.0 \times 1.0 \times 1.0$).

### *Imaging data analysis*

Data analysis was performed with SPM2 from the Wellcome Department of Cognitive Neurology, London. MNI coordinates

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[1] This is possible with Chinese characters because they use a spatial rather than phonologically related orthographic system. In English, orthographic regularity refers to the particular combination of vowels and consonants, whereas in Chinese, orthographic regularity depends on the particular spatial organization of phonetic and radical parts, which can be used only in some specific locations of a character, either left and right or top and bottom (e.g., in real characters AB and CD, parts A and C can be only in the left side while B and D can be only in the right side). So we can create orthographically legal but unpronounceable pseudo characters by keeping these parts in their original positions and changing their combinations (e.g., pseudo characters AD and CB are orthographically legal but unpronounceable).

(Friston et al., 1995) were transferred into Talairach coordinates (Talairach and Tournoux, 1988) according to the criteria specified by http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml. The first two scans were discarded from the analysis to eliminate nonequilibrium effects of magnetization. Scans were first realigned, normalized, smoothed ($6\times6\times8$ mm, Gaussian spatial filter), and filtered (high-pass filter set at 128 s, low-pass filter achieved by convolution with hemodynamic response function). The resulting images had cubic voxels of $2\times2\times2$ mm$^3$.

We performed a group-level random effects analysis by conducting a one-sample *t*-test across all individual participants. An overall main effect of stimulus was examined by contrasting each of four experimental stimuli with the fixation stimulus. Main effects for all three types of characters were investigated by contrasting them with the Checkerboard. Both of these contrasts used an uncorrected voxelwise threshold of $P<0.001$ with a corrected $P<0.05$ for cluster extent. Hierarchical subtractions between three types of characters were also performed to examine differential levels of the implicit processing of Chinese characters. Since the contrast effects between the three types of characters were weaker than those contrasting the three types of characters with the Checkerboard, the threshold was set lower at uncorrected $P<0.02$ with a corrected $P<0.05$ for cluster extent (Cohen et al., 2004; Dehaene et al., 2004a, 2001). In order to verify the consistency of activations in the occipital–temporal region among individual participants, we also conducted an individual analysis for each of 14 participants with a threshold of uncorrected $P<0.005$. We looked for the VWFA in each individual participant using the contrast of Pseudo vs. Artificial characters (Cohen et al., 2002).

## Results

### *Behavioral results*

Table 1 shows both reaction time and error rate (mean±SD) data for the four types of stimuli. Responses with a RT > 800 ms or RT < 200 ms were cut off as outliers (4 trials, 1.25% of all responses). A Size (Large vs. Small) × Character Type (Artificial vs. Pseudo vs. Real) ANOVA was conducted on both reaction time and error rate data. Results showed that two main effects in error rate data were significant: Size: $F(1, 13)=7.76$, $P<0.05$ (Small: 7.54%, Large: 4.09%) and Character Type: $F(2, 26)=3.56$, $P<0.05$ (Real: 5.60%, Pseudo: 7.31%, Artificial: 4.54%), but no significant interaction was found. Neither main effect (Size, Character Type) nor the interaction was significant in RT data.

### *Imaging results overall pattern of the four experimental stimuli vs. fixation stimulus*

As we can see from Fig. 2, when contrasted with the fixation stimulus, all four types of stimuli activated a large scale of neuronal networks including bilateral frontal cortex, parietal lobe and occipital–temporal regions, especially the right frontal region. In addition, the three types of characters yielded stronger activations in the left frontal cortex and bilateral occipital–temporal regions than the Checkerboard.

Table 1
Error rate and RT data of four type of stimuli in two sizes

| Type | Error rate (%) | | RT (ms) | |
|---|---|---|---|---|
| | Large size | Small size | Large size | Small size |
| Real | 3.41±4.24 | 7.78±5.31 | 458.37±42.16 | 482.20±38.89 |
| Pseudo | 4.30±4.09 | 10.32±6.76 | 462.07±38.81 | 478.38±35.02 |
| Artificial | 4.55±5.22 | 4.52±3.62 | 460.96±38.35 | 468.13±37.05 |
| Checkerboard | 2.36±3.51 | 4.90±3.06 | 444.13±26.85 | 460.71±37.34 |

### *Three types of characters (Real, Pseudo, Artificial) vs. Checkerboard*

All three types of characters, as compared to the Checkerboard, activated similar patterns in occipital–temporal regions but different regions in frontal and parietal regions (see Fig. 3, Table 2). Specifically, contrasted with the Checkerboard, all three types of characters showed no activations in the right frontal region (see Fig. 3, Table 2). In addition, Real characters elicited significant activations in the left middle frontal gyrus (BA 9), the left superior parietal lobe (BA 7), and the left parahippocampal gyrus. Pseudo characters showed activations similar to Real characters in the left middle frontal gyrus (BA 9) and the left superior parietal lobe (BA 7), but they also showed significant activations in the left inferior frontal gyrus (BA 47), the right caudate, the right parietal angular gyrus (BA 39), the right anterior cingulate cortex (BA 32), and bilateral thalamus. Finally, like Pseudo characters, Artificial characters also showed significant activations in the right caudate, but they also yielded a unique activation in the right precuneus.

### *Comparisons within the three character types (Real, Pseudo, Artificial)*

The internal comparisons among three types of characters illustrated more details about the implicit processing of Chinese characters (Fig. 4, Table 3).

Compared with Artificial characters, Pseudo and Real characters generated activations in many areas in the left hemisphere, especially the left middle frontal gyrus (BA 9) and the left middle fusiform gyrus (BA 37). In addition, Real characters also activated a number of regions in the language processing network, including the left postcentral gyrus (BA 4), the left inferior frontal gyrus (BA 9), the left inferior parietal lobe (BA 40), the left inferior temporal gyrus (BA 37), and the left superior temporal gyrus (BA 39). Different from Real characters, Pseudo characters activated the left frontal precentral gyrus (BA 6) and some regions in the right hemisphere including thalamus, caudate, claustrum, and extra-nuclear. Contrasted with Real characters, Pseudo and Artificial characters showed greater activation in bilateral middle occipital gryus (BA 19) and the right superior parietal lobe (BA 7). Pseudo characters also activated the left inferior frontal gyrus (BA 47) and lentiform nucleus, bilateral thalamus, anterior cingulate (BA 32), fusiform gyrus (BA 37), and a number of right hemisphere regions including the caudate, extra-nuclear, medical frontal gyrus (BA 10), insula, superior frontal gyrus (BA 10), middle frontal gyrus (BA 9), and inferior temporal gyrus (BA 20). Artificial characters also activated the left cuneus (BA 19), the right parietal postcentral gyrus (BA 2), precuneus (BA 19), bilateral fusiform gyrus (BA 19, BA 37), and inferior temporal gyrus. No activation was found in the Real vs. Pseudo and Artificial vs. Pseudo contrasts.

One noticeable activation, as we hypothesized, was in the left middle fusiform gyrus (−44, −51, −16, BA 37) (Figs. 4 and 5, Table 3) identified in the Pseudo vs. Artificial contrast, a region that is repeatedly recognized in English studies as VWFA (Cohen

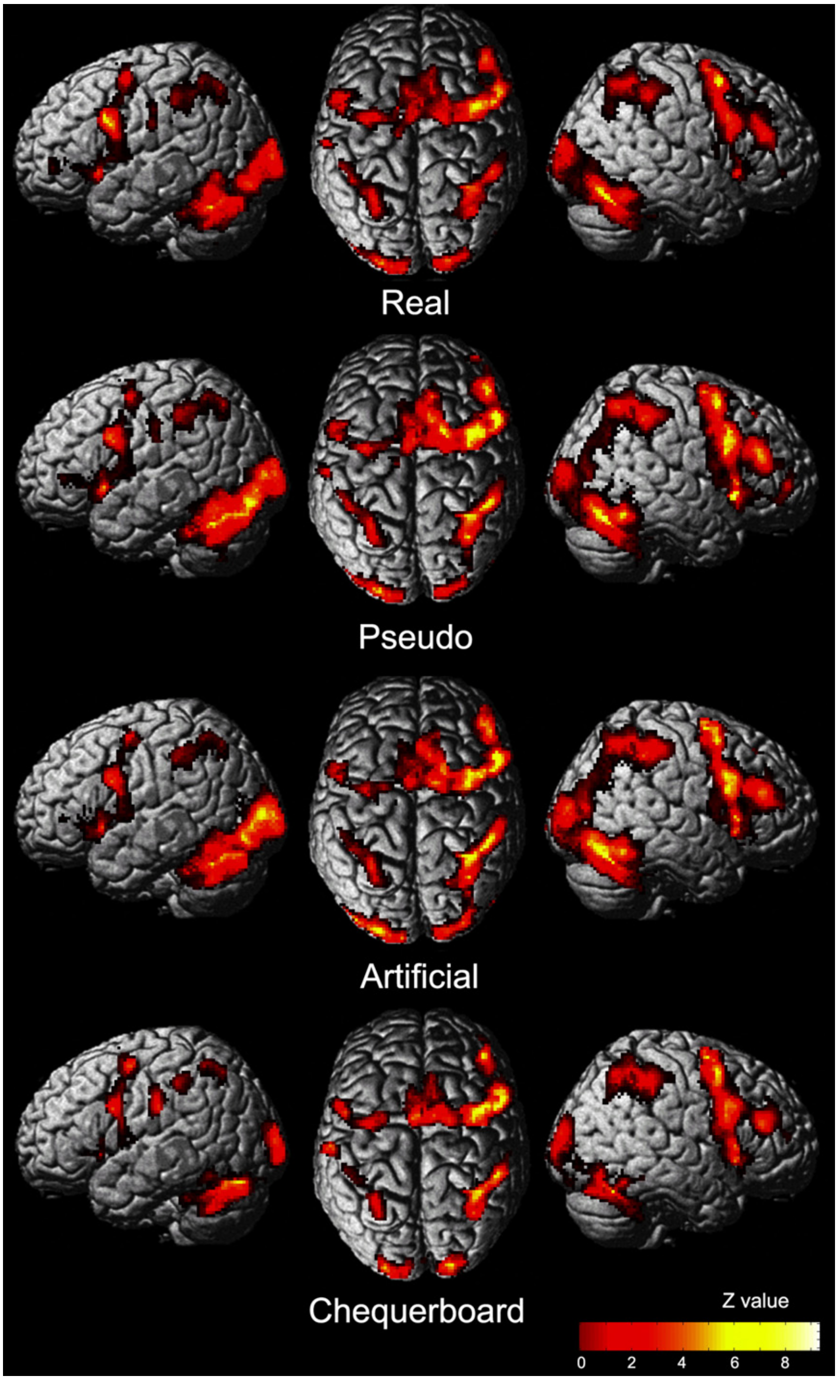

Fig. 2. Brain regions with significant activity for all four experimental stimuli as indexed to the fixation stimulus (group analyses; voxelwise threshold of $P<0.001$, with a corrected $P<0.05$ for cluster extent).

et al., 2000, 2002, 2003; Dehaene et al., 2002, 2001; McCandliss et al., 2003).

### *Individual analysis of Visual Word Form Area*

To confirm the localization of VWFA, we found in the group analysis of Pseudo vs Artificial contrasts (−44, −51, −16) and compare it with the VWFA found in alphabetic scripts studies, we conducted an individual analysis of this region focusing specifically on Pseudo vs. Artificial characters contrast with a voxelwise threshold of uncorrected $P<0.005$ (Cohen et al., 2002) (Table 4). Thirteen of fourteen participants showed significant activation in the immediate vicinity of the peak isolated in the group analysis. Results from this contrast indicated that the coordinates of the Visual Word Form Area found in our study was $x=-45$, $y=-54$, $z=-15$, with a standard deviation of 5 mm, 4 mm, and 5 mm, respectively. This result was quite impressive in its similarity to VWFA localized in alphabetic scripts, such as $x=-43$, $y=-54$, $z=$

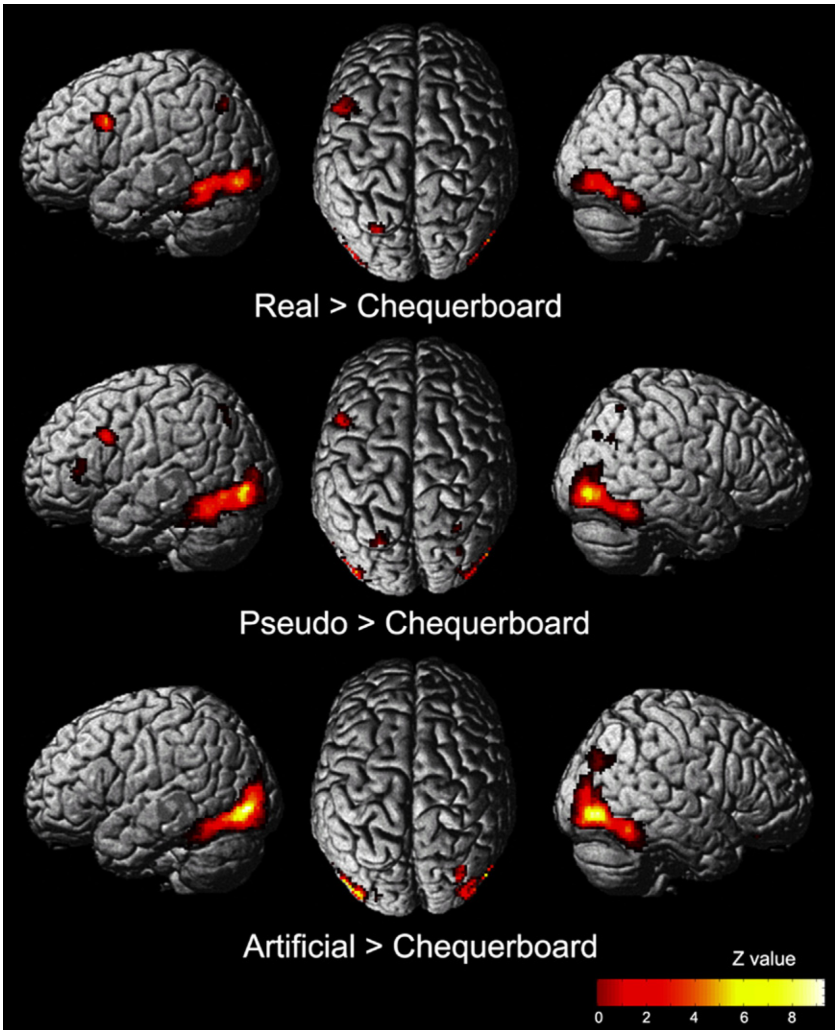

Fig. 3. Brain regions with significant activity for three types of characters as indexed to the Checkerboard (voxelwise threshold of $P<0.001$, with a corrected $P<0.05$ for cluster extent).

−12, with a standard deviation of 5 mm in Cohen et al. (2000) and $x=-42$, $y=-57$, $z=-15$ in Cohen et al. (2002), experiment 2.

## Discussion

The main purpose of the present study was to investigate whether or not a specific Visual Word Form Area could be identified in implicit Chinese character processing by comparing orthographically legal Real and/or Pseudo characters with orthographically illegal Artificial characters using a size judgment task.

In the behavioral results, we found a significant Character Type effect in the error rate data, such that participants made more errors judging the size of Real and Pseudo characters than that of Artificial characters. However, from Table 1, we can see that the main effect of Character Type in error rate largely comes from the small Real and small Pseudo characters (Real, 7.78%±5.31; Pseudo, 10.32%±6.76; Artificial, 4.52%±3.62) rather than the large Real and large Pseudo characters (Real, 3.41%±4.24; Pseudo, 4.30%±4.09; Artificial, 4.55%±5.22). We think this might be because some small size Real or Pseudo characters are hard to be distinguished from large size characters. Although such difficulty with Small Real and Pseudo characters might indeed impact the fMRI results, we think the influence is small, because (1) there is no difference in RT data, which means participants spend similar amounts of time on all characters no matter whether they judge them as large or small, and( 2) we used unique characters for large and small size characters and averaged over all of them in the fMRI analysis, so the influence from a few characters is minimized. However, the Character Type effect could still be considered one weakness in our study that has an impact on our fMRI results. Specifically, one might interpret the significant brain activations in Real and/or Pseudo vs. Artificial contrasts to have been caused by participants needing more effort to judge the size of these two types of characters.

In the fMRI results, all of the contrasts between the four experimental stimuli and the fixation stimulus showed a large are of activation in the right frontal cortex (Fig. 2), which might indicate that the right frontal cortex activates the basic sensorimotor processing involved in a key press response, decision-making processing, or other more general functions that were involved in processing all four types of stimuli such as visual

Table 2
Brain regions showing significant activations between the three types of characters and checkerboard

| Contrast | BA | *P* | Voxel | *x* | *y* | *z* | *Z* |
|---|---|---|---|---|---|---|---|
| *Real>Checkerboard* | | | | | | | |
| L inferior occipital G | 19 | <0.001 | 1367 | −44 | −76 | −6 | 5.45 |
| L superior parietal L | 7 | 0.002 | 187 | −26 | −64 | 42 | 5.09 |
| L parahippocampal G | | 0.013 | 131 | −32 | −7 | −23 | 4.31 |
| L middle frontal G | 9 | <0.001 | 317 | −40 | 11 | 29 | 4.25 |
| R middle occipital G | 19 | <0.001 | 853 | 48 | −78 | −3 | 5.10 |
| *Pseudo>Checkerboard* | | | | | | | |
| L inferior occipital G | 18 | <0.001 | 1883 | −42 | −80 | −6 | 5.44 |
| L superior parietal L | 7 | <0.001 | 220 | −26 | −64 | 38 | 4.08 |
| L middle frontal G | 9 | 0.001 | 185 | −50 | 17 | 30 | 4.66 |
| L inferior frontal G | 47 | 0.037 | 98 | −36 | 33 | 2 | 4.30 |
| L thalamus | | 0.001 | 182 | −22 | −19 | 12 | 4.13 |
| R inferior occipital G | 19 | <0.001 | 1505 | 46 | −78 | −3 | 5.63 |
| R parietal angular G | 39 | 0.001 | 205 | 32 | −61 | 33 | 3.82 |
| R anterior cingulate | 32 | 0.035 | 99 | 20 | 35 | 6 | 3.80 |
| R caudate | | 0.001 | 206 | 16 | 7 | 20 | 4.32 |
| R thalamus | | 0.008 | 135 | 22 | −17 | 12 | 4.25 |
| *Artificial>Checkerboard* | | | | | | | |
| L inferior occipital G | 18 | <0.001 | 1907 | −42 | −80 | 2 | 5.69 |
| R inferior temporal G | 19 | <0.001 | 1890 | 50 | −72 | −1 | 5.65 |
| R precuneus | 19 | <0.001 | 319 | 30 | −70 | 33 | 4.30 |
| R caudate | | 0.004 | 176 | 14 | 25 | −6 | 4.39 |

All the activated voxels in the left temporal lobe were extended (voxelwise threshold of $P<0.001$, with a corrected $P<0.05$ for cluster extent).

working memory and attentional load (Corbetta and Shulman, 2002). This interpretation is supported by the finding that all three types of characters showed no activation in the right frontal region when contrasted with the Checkerboard (see Fig. 3, Table 2).

### *Fine-grained to the physical appearance of words*

In the three types of characters vs. Checkerboard contrasts, orthographic Real and Pseudo characters generate additional language network activations in frontal and parietal regions (BA 9 and BA 7), when compared with nonorthographic Artificial characters (Fig. 3, Table 2). However, all three types of characters activated a large extent of the bilateral occipital–temporal regions (Fig. 3). This is rather surprising for the Artificial characters, as they do not contain orthographic regularities. This finding was further supported by direct comparisons of the Artificial vs. Real characters, which also showed strong activations in the bilateral middle occipital gyrus (BA 18, BA 19) and bilateral occipital fusiform gyrus (BA 19) without any left dominant activation patterns (Fig. 4, Table 3). These results are also compatible with many other Chinese characters and Japanese Kanji studies that have found strong bilateral occipital–temporal region activation (Kuo et al., 2001; Siok et al., 2004; Tan et al., 2001b, 2000; Thuy et al., 2004).

In alphabetic scripts, the VWFA is known to be tuned to the shape of letters, relative to visually equivalent pseudo-letters or digits (Cohen and Dehaene, 2004). Stronger activations in the left fusiform gyrus were observed in the contrast of consonant strings vs. false-font characters (Petersen et al., 1990; Price et al., 1996), alphabetic stimuli (words and consonants) vs. Checkerboard (Cohen et al., 2002), and strings of letters vs. digits (Polk et al., 2002). However, as a logographic script, Chinese characters are both more numerous and more varied than alphabetic scripts in visual shape since they have hundreds of sublexical components rather than 26 letters, and the organization of these character components is two-dimensional (left to right, top to bottom) instead of one-dimensional (left to right). Theoretically, then, it would not be as easy for the left middle fusiform gyrus to be the sole area for completing this kind of fine-grained function in Chinese character components as it would be for English letters. Although the Artificial characters we used contain no orthographic regularity, they still retain visual aspects of Chinese characters such as strokes and the radical components. Thus, our results, as well as many other findings might indicate that the fine visual distinctions required in recognizing Chinese characters may be performed by the bilateral middle occipital gyrus and occipital fusiform gyrus rather the left fusiform gyrus alone. We propose that this would be a special feature for logographic scripts in contrast to alphabetic scripts, and it might be a result of the visual complexity or other features specific to logographic scripts. For example, because of the relative transparency of semantic vs. phonological information (Siok et al., 2004), logographic characters might have stronger links with bilateral semantic representations, whereas alphabetic characters might have stronger links with left-sided phonological representations.

### *Orthographic regularity*

The most interesting finding is the left middle fusiform gyrus (Figs. 4 and 5, Table 3) activation identified in the Pseudo vs. Artificial contrast, as well as the consistency of its coordinates among individual participants (Table 4). Since the Pseudo characters we used here are orthographically legal but unpronounceable, they would provide information on pure orthographic processing when contrasted with Artificial characters that are visually similar but orthographically illegal.

In English, a consistent result among diverse studies about VWFA is that it responds more to words or pseudo-words than to random consonant strings that lack orthographic restrictions (Beauregard et al., 1997; Buchel and Price, 1998; Cohen et al., 2002; Price et al., 1996; Rees et al., 1999; Xu et al., 2001), which implies that the VWFA has become sensitive to orthographic rules of the English script. Although many researchers have investigated the orthographic processing of logographic scripts, none has revealed the existence of VWFA in logographic scripts using direct contrasts between Real or Pseudo characters with orthographically illegal figures or strings. For example, Kuo et al. (2004) did not find any occipital–temporal region activation in the Real Characters and Pseudo characters vs. meaningless figures (Korean characters) contrast using a form judgment task. In studies with Japanese Kanji as stimuli, only a few (e.g., Thuy et al., 2004) found left occipital–temporal activation in the contrast between Kanji characters and scrambled characters. Nevertheless, the critical region in processing Kanji is in the posterior inferior temporal cortex (PITC) rather than the fusiform gyrus (Thuy et al., 2004). To our knowledge, our study is the first one that identifies the VWFA in Chinese character processing using a contrast between linguistic and nonlinguistic stimuli.

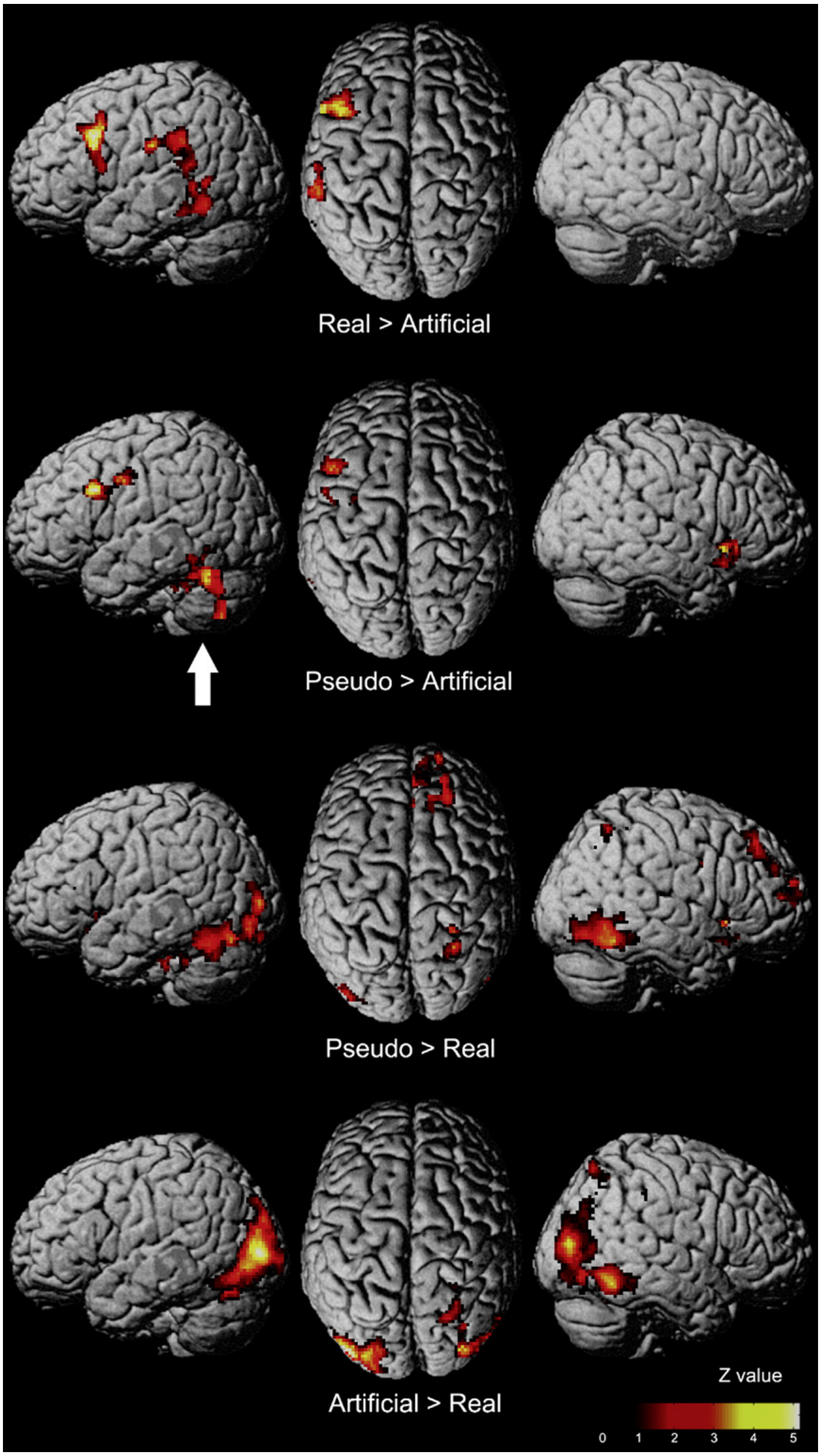

Fig. 4. Brain regions with significant activity for the comparison within three types of characters. The white arrow indicates the left middle fusiform gyrus (−44, −51, −16, BA 37) identified by the Pseudo vs. Artificial contrast (group analyses; voxelwise threshold of $P<0.02$, with a corrected $P<0.05$ for cluster extent).

However, it is necessary to note that results from our current design also have some limitations. First of all, as some researchers have argued, reading is a parallel distributed process (Rumelhart and McClelland, 1986), which evokes activation from numerous brain areas from visual to language regions, and these areas interact with each other (Kronbichler et al., 2004; Price and Devlin, 2003). Other researchers further suggest that our knowledge about letter combinations arises from interactions between orthographic,

Table 3
Brain regions showing significant differences by comparisons among three types of characters (voxelwise threshold of $P<0.02$, with a corrected $P<0.05$ for cluster extent)

| Contrast | BA | *P* | Voxel | *x* | *y* | *z* | *Z* |
|---|---|---|---|---|---|---|---|
| *Real>Pseudo* | | | | | | | |
| (none) | | | | | | | |
| *Real>Artificial* | | | | | | | |
| L middle frontal G | 9 | 0.033 | 633 | −48 | 19 | 32 | 3.58 |
| L inferior frontal G | 9 | | | −57 | 17 | 25 | 3.44 |
| L postcentral G | 4 | 0.018 | 708 | −51 | −16 | 28 | 3.44 |
| L inferior parietal L | 40 | | | −61 | −33 | 31 | 3.42 |
| L inferior temporal G | 37 | | | −59 | −53 | −4 | 3.27 |
| L fusiform G | 37 | | | −50 | −41 | −9 | 3.18 |
| L superior temporal G | 39 | | | −53 | −52 | 6 | 3.10 |
| *Pseudo>Artificial* | | | | | | | |
| L frontal precentral G | 6 | 0.037 | 607 | −53 | 2 | 37 | 3.52 |
| L middle frontal G | 9 | | | −48 | 15 | 29 | 3.40 |
| L fusiform G | 37 | 0.005 | 841 | −44 | −51 | −16 | 3.30 |
| R thalamus | | 0.011 | 742 | 2 | −5 | 8 | 3.72 |
| R caudate | | | | 12 | 1 | 18 | 3.55 |
| R claustrum | | 0.005 | 837 | 34 | −2 | −2 | 3.54 |
| R extra-nuclear | 13 | | | 28 | 18 | −8 | 3.25 |
| *Pseudo>Real* | | | | | | | |
| L fusiform G | 37 | <0.001 | 2364 | −48 | −59 | −14 | 3.71 |
| L inferior occipital G | 19 | | | −44 | −82 | −4 | 3.21 |
| L inferior frontal G | 47 | | | −22 | 33 | −5 | 3.73 |
| L thalamus | | | | −12 | −6 | 6 | 3.59 |
| L lentiform nucleus | | | | −26 | −8 | 4 | 3.42 |
| L anterior cingulate | 32 | | | −12 | 30 | 22 | 3.39 |
| R lentiform nucleus | | <0.001 | 7109 | 24 | 17 | −4 | 4.74 |
| R extra-nuclear | 13 | | | 26 | 17 | −8 | 4.66 |
| R thalamus | | | | 6 | −10 | 4 | 4.34 |
| R caudate | | | | 14 | 12 | 16 | 4.25 |
| R medial frontal G | 10 | | | 22 | 49 | 7 | 3.86 |
| R anterior cingulate | 32 | | | 12 | 36 | 17 | 3.39 |
| R superior parietal L | 7 | | | 30 | −48 | 41 | 3.35 |
| R precuneus | 7 | | | 28 | −52 | 50 | 3.35 |
| R insula | | | | 42 | −23 | 16 | 3.23 |
| R superior frontal G | 10 | | | 22 | 50 | 25 | 3.15 |
| R middle frontal G | 9 | | | 24 | 41 | 35 | 3.10 |
| R fusiform G | 37 | 0.001 | 1107 | 51 | −59 | −11 | 3.61 |
| R inferior temporal G | 20 | | | 53 | −53 | −14 | 3.54 |
| *Artificial>Pseudo* | | | | | | | |
| (none) | | | | | | | |
| *Artificial>Real* | | | | | | | |
| L middle occipital G | 18 | <0.001 | 2989 | −40 | −85 | 10 | 4.57 |
| | 19 | | | −44 | −77 | 6 | 3.95 |
| L fusiform G | 19 | | | −28 | −67 | −10 | 3.92 |
| | 37 | | | −34 | −61 | −9 | 3.17 |
| L lingual G | 18 | | | −20 | −74 | −3 | 3.61 |
| L cuneus | 19 | | | −22 | −84 | 39 | 3.60 |
| L inferior temporal G | 19 | | | −51 | −72 | −1 | 3.60 |
| R middle occipital G | 19 | <0.001 | 3529 | 34 | −81 | 15 | 4.42 |
| R fusiform G | 19 | | | 30 | −57 | −11 | 4.29 |
| | 37 | | | 34 | −49 | −9 | 4.26 |
| | 20 | | | 28 | −42 | −18 | 3.16 |
| R inferior temporal G | | | | 55 | −55 | −11 | 4.10 |
| R parietal postcentral G | 2 | | | 38 | −27 | 36 | 4.06 |
| R superior parietal L | 7 | | | 22 | −65 | 60 | 3.50 |
| R precuneus | 19 | | | 32 | −68 | 31 | 3.36 |

semantic, and phonological processing without any explicit word form representations (Plaut et al., 1996; Seidenberg and McClelland, 1989). This argument is supported by imaging studies showing activations of the VWFA in a broad set of experimental conditions, including reading, but also tactile and auditory word processing, object perception, naming, perception of "socially interactive" movements, and so on (Price and Devlin, 2003). None of these arguments against the VWFA hypothesis were directly examined in our current design as they go beyond the question of whether the VWFA is a universal as opposed to a language-specific area for processing visual information related to reading. Therefore, the interpretation of our results has this as a limitation, but no more so than do similar studies with alphabetic systems.

Secondly, our use of Chinese pseudo characters might also raise some potential problems. In our study, Pseudo characters show stronger activations not only than Artificial characters, but also than Real characters in many regions, especially the right frontal and bilateral occipital–temporal regions (Fig. 4, Table 3). Although Pseudo characters are unpronounceable and meaningless at the holistic level, they indeed contain components that offer cues to both pronunciation and meaning. Thus the heavy involvement of the left middle fusiform region in the processing of Pseudo characters may be relevant to the automatic processing of sounds and meanings of the components.

Finally, although we showed that the left middle fusiform gyrus is crucial for orthographic processing of Chinese characters, whether this area is specialized only for orthographic analysis still remains unclear. Studies have found that the VWFA is not a single function unit specific to only one particular function, but is part of a more complicated functional group that processes information across multiple levels (Cohen and Dehaene, 2004; Price and Devlin, 2003). The fusiform cortex can be decomposed into smaller subareas from posterior to anterior with specific processing specializations. In addition to the middle subpart that is labeled as VWFA, the posterior subpart, observed bilaterally, likely holds locations of sublexical information (Dehaene et al., 2004b) and the left part also modulates phonological processing (Dietz et al., 2005), whereas the more anterior subpart ($y=-43$ on average) has been suggested to be sensitive to an increased task demand for semantic processing of visual or auditory words (Cohen et al., 2002; Price and Devlin, 2003). Similar results have also been found in logographic scripts. A cross-script study on subliminal priming between Kanji and Kana, for instance, found that the priming effect was associated with suppression of repetition in the left inferior temporal cortex anterior and dorsal to the Visual Word Form Area (Nakamura et al., 2005). In our study, this functional diversity was apparent in the internal comparisons of three types of characters (Fig. 4, Table 3). In addition to the middle subpart of VWFA, we found in the Pseudo vs. Artificial contrast ($y=-51$) that the bilateral posterior fusiform gyrus was also activated in the Artificial vs. Real contrast ($y=-67$). Compared with Real characters, the Artificial characters required more difficult location invariant processing since the Artificial characters contain unreadable sublexical components but were located in novel positions. Meanwhile, the anterior subpart activation was found in the Real vs. Artificial contrasts ($y=-41$), indicating additional implicit semantic processing for the Real character.

Taken together, although we found that the left middle fusiform gyrus is associated with orthographic processing in the case of

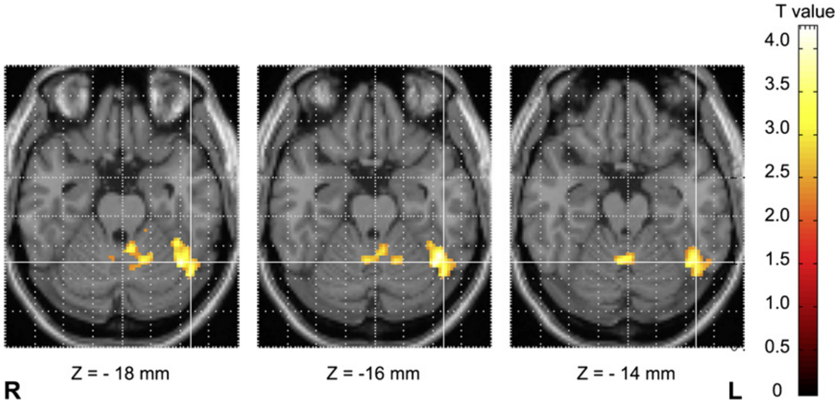

Fig. 5. Brain slices showed the left middle fusiform gyrus (−44, −51, −16, BA 37) identified by the Pseudo vs. Artificial contrast (group analyses; voxelwise threshold of $P < 0.02$, with a corrected $P < 0.05$ for cluster extent).

written Chinese characters, our results do not rule out alternative explanations or additional functions and contributions of this region.

### Orthographic processing for Chinese characters

In the present study, the VWFA of the left middle fusiform (BA 37) showed stronger activation for orthographical Real and Pseudo characters than nonorthographic Artificial characters, which indicates that the VWFA plays as important a role in orthographical processing of Chinese characters as it does for alphabetic scripts.

However, the VWFA alone may not be enough for orthographical processing of Chinese characters. Different writing systems code aspects of spoken language in very different ways; as a result, there must be variations in the orthographic processing of different languages. An obvious distinction between an alphabetic script and the Chinese script is that the former consistently maps graphemes to phonemes whereas the latter maps a logographic character to a meaningful unit such as a morpheme or word (Bolger et al., 2005; Tan et al., 2005). Previous neuroimaging studies have shown that the conversion of orthographical to phonological processing (grapheme-to-phoneme conversion) in processing alphabetic stimuli was performed by left posterior sites of temporoparietal regions (Siok et al., 2003, 2004; Tan et al., 2005), whereas Chinese stimuli need the left middle frontal gyrus for both conversion of graphic form (orthography) to syllable, and other operations concerning orthographic-to-semantic mappings (Siok et al., 2004; Tan et al., 2001a, 2005, 2003). Thus, in addition to the left middle fusiform gyrus, the left middle frontal gyrus is also supposed to be activated in Chinese orthographic processing. Interestingly, this feature of Chinese character processing was also established in our results. Hyperactivity in the left middle frontal cortex (BA 9) was found for both orthographic Real and Pseudo characters when contrasted with Checkerboard (Fig. 3, Table 2). In contrast, nonorthographic Artificial characters showed no activation in this region. This tendency was confirmed by contrasting Real and Pseudo characters with Artificial characters, which also highlights the left middle frontal cortex (BA 9) (Fig. 4, Table 3). These results indicated that in addition to the VWFA being located in the left middle fusiform gyrus (BA 37), the left middle frontal cortex (BA 9) might also be an indispensable area for orthographic processing of Chinese characters, as opposed to alphabetic orthographies. Moreover, these two regions might consist of a neural circuit for orthographic–semantic transfer in Chinese character processing (Siok et al., 2004). Nonetheless, details of the relationships between these areas are fruitful issues for further investigations.

Table 4
Individual analysis of Visual Word Form Area revealed by Pseudo vs. Artificial contrast in fourteen participants (voxelwise threshold of $P < 0.005$)

| Participants | Pseudo > Artificial | | | |
|---|---|---|---|---|
| | TC | | | Z |
| | x | y | z | |
| 1 | −40 | −59 | −22 | 3.21 |
| 2 | −46 | −47 | −13 | 2.64 |
| 3 | −50 | −55 | −16 | 2.66 |
| 4 | −50 | −59 | −17 | 2.97 |
| 5 | −50 | −57 | −12 | 3.68 |
| 6 | −42 | −53 | −7 | 4.04 |
| 7 | −42 | −51 | −16 | 2.62 |
| 8 | −46 | −55 | −17 | 4.13 |
| 9 | −50 | −61 | −22 | 3.21 |
| 10 | −51 | −48 | −18 | 3.39 |
| 11 | | | | |
| 12 | −44 | −51 | −14 | 2.66 |
| 13 | −34 | −57 | −6 | 2.59 |
| 14 | −40 | −53 | −9 | 4.72 |
| Mean | −45 | −54 | −15 | |
| SD | 5 | 4 | 5 | |

## Conclusion

To conclude, our experiment found that activity in the left middle fusiform gyrus (BA 37) is stronger for Real and Pseudo characters than for Artificial characters. Moreover, despite differences in scripts, tasks, and language between our study and previous studies, the coordinates of VWFA we found in implicit processing of Chinese characters are similar to the VWFA localized in alphabetic scripts.

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