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RESEARCH ARTICLE

The orthographic sensitivity to written Chinese in the occipital-temporal cortex

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Abstract Previous studies have identified an area in the left lateral fusiform cortex that is highly responsive to written words and has been named the visual word form area (VWFA). However, there is disagreement on the specific functional role of this area in word recognition. Chinese characters, which are dramatically different from Roman alphabets in the visual form and in the form to phonological mapping, provide a unique opportunity to investigate the properties of the VWFA. Specifically, to clarify the orthographic sensitivity in the mid-fusiform cortex, we compared fMRI response amplitudes (Exp. 1) as well as the spatial patterns of response across multiple voxels (Exp. 2) between Chinese characters and stimuli derived from Chinese characters with different orthographic properties. The fMRI response amplitude results suggest the existence of orthographic sensitivity in the VWFA. The results from multi-voxel pattern analysis indicate that spatial distribution of the responses across voxels in the occipitotemporal cortex contained discriminative information between the different types of character-related stimuli. These results together suggest that the orthographic rules are likely represented in a distributed neural network with the VWFA containing the most specific information regarding a stimulus' orthographic regularity.

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Keywords Visual word form area (VWFA) · Orthography · Multi-voxel pattern analysis (MVPA) · Chinese character

Abbreviations

VWFA Visual word form area
MVPA Multi-voxel pattern analysis

Introduction

There is strong evidence for a specific involvement of the ventral occipitotemporal cortex in visual word processing, especially for a small area in the left mid-fusiform region, termed visual word form area (VWFA) (Cohen et al. 2000, 2002). While the majority of studies were carried out with alphabetic words in passive viewing or one-back repetition tasks (Fiez and Petersen 1998; Dehaene et al. 2001; Price and Mechelli 2005), more recent studies suggest that the location of the VWFA is independent of script type (e.g., alphabetic vs. Chinese words) and task manipulation (e.g., passive viewing vs. active reading) (Bai et al. 2011;

Ma et al. 2011; Liu et al. 2008; Xu et al. 2012), or even input modality (Reich et al. 2011).

A fundamental question remains open regarding what information of written words is represented and computed at the VWFA. While many authors suggest that this cortical region is mainly used for processing orthographic information (e.g., Baker et al. 2007), others emphasize its role in linking the visual form to linguistic functions, such as phonology (Price and Devlin 2011) and lexical processing (Kronbichler et al. 2004, 2007; Glezer et al. 2009). However, because of the systematic mapping between orthography and phonology in alphabetic scripts, it is difficult to dissociate orthographic and linguistic processing with alphabetic stimuli. In contrast, the mapping between visual and phonological forms is relatively arbitrary in written Chinese, making it possible to examine "pure" effects of orthographic properties with minimal involvement of phonology.

In experiment 1 of the present study, we took advantage of this unique property of Chinese characters and investigated whether the orthographic or lexical property is represented in the VWFA. We adopted three types of stimuli based on Chinese characters, namely real characters, pseudo characters, and false characters (Fig. 1a). They were structurally matched but differed in their lexical and orthographic properties. Real characters are common left–right structured characters. A pseudo character is formed by two real radicals each in its commonly occupied position, but the two never would appear together in a real character. A false character is also made up with two real radicals, but they occupy the unusual positions (i.e., radicals normally appear on the left side in real characters are now placed on the right side of false characters). A contrast between real vs. pseudo characters reflects lexical sensitivity, while the contrast between real/pseudo vs. false characters reflects orthographic sensitivity to the radical position.

The position of radicals is one of the orthographic properties of Chinese characters. The orthographic system of written Chinese can also be described at a number of different levels, including strokes, radicals, and characters. The processes involved in character recognition include the processing of these different levels of orthography (Peng and Wang 1997; Chen et al. 1996; Taft and Zhu 1997; Li and Chen 1999; Taft et al. 1999; Ding et al. 2004; Feldman and Siok 1997). Thus, by manipulating the different levels of orthographic properties of Chinese characters, it affords the opportunity for more detailed investigation of neural correlates of orthographic processing.

In experiment 2, we adopted the multi-voxel pattern analysis (MVPA) (Haxby et al. 2001) to characterize activation patterns in a number of regions from V1 to the VWFA. Given that the different types of character-related stimuli may be differentially represented in these regions at spatial scales finer than traditionally defined ROIs (e.g., LOC or VWFA), the MVPA approach is particularly useful and could potentially reveal information represented in these regions (Bandettini 2009; Mur et al. 2009). To obtain a more comprehensive understanding of the orthographic sensitivity through the hierarchical system for visual word processing, we analyzed the activation patterns in V1, LOC and lateral, center and medial parts of the mid-fusiform.

Methods and materials

All experiments and procedures were approved by the Institutional Review Board at the Institute of Psychology,

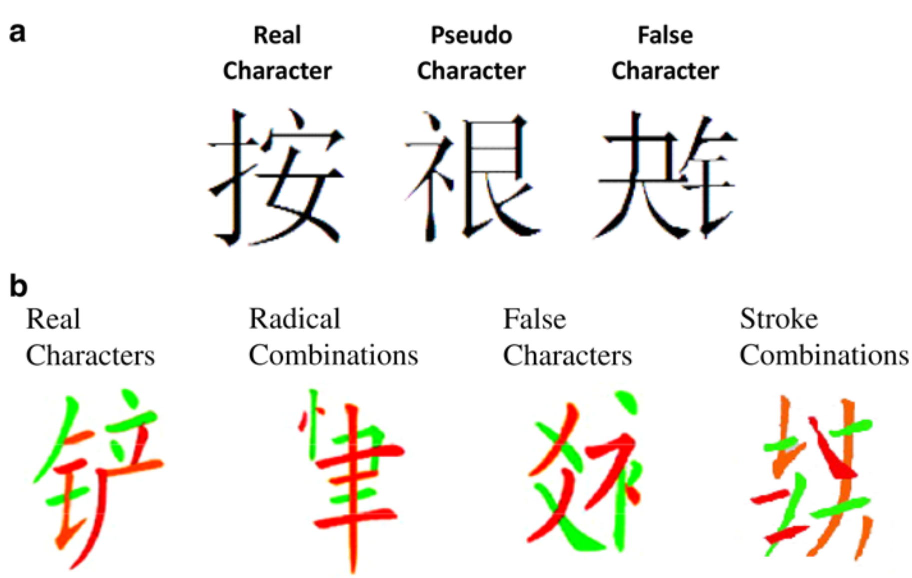

Fig. 1 **a** Example of the three types of the Chinese character-related stimuli used for the event-related runs in experiment 1. **b** Examples of the four types of stimuli used in experiment 2

Chinese Academy of Sciences. All participants gave written, informed consent before taking part in the experiment.

Subjects

Eleven and 8 native Chinese speakers took part in the experiment 1 and experiment 2, respectively. They were aged between 21 and 32 years, in college or college educated. All participants were right-handed, had normal or corrected-to-normal vision.

Stimuli

In both experiments 1 and 2, two scans were first performed to localize the VWFA, in which observers viewed Chinese characters, line drawings of common objects, and non-famous Chinese faces in blocked-design runs. Real, pseudo, and false characters then were used in event-related design runs to investigate the VWFA's sensitivity to orthographic and lexical information (Fig. 1a). Pseudo characters are incorrect pairing of radicals each in their legitimate locations. False characters are combination of radicals each in their illegitimate locations. Line drawings were also used as a type of control stimulus.

For the experiment 2, four types of stimuli derived from Chinese characters were used, including real characters, radical combinations, false characters, and stroke combinations. In addition, non-famous Chinese faces were also included as a type of control stimulus. These stimuli were presented in block-design runs (Fig. 1b). From stroke combinations to real characters, the stimuli meet increasing numbers of orthographic rules. In the "stroke combination" stimuli, the individual strokes could quickly lose their identity when intersecting with each other. To preserve the visual identity of individual strokes, we used three different colors to encode the strokes (the colored strokes were used to construct the other three types of character-related stimuli, so that they could not be distinguished based on colors). Radical combinations are composed of two radicals from real left–right structure characters. Two radicals are combined randomly and placed in spatial relationships using different spatial scales that discourage their combination into a single character-like unit, with the intention that the two radicals remained mostly independent of each other. The real characters and false characters were the same as the ones used in experiment 1 except the use of colored strokes. A full list of the character-like stimuli is provided in Supplementary Materials (Fig. S2). In addition, a set of unfamiliar Chinese face stimuli was also used, activation to which provided robust localization landmarks, the face fusiform area (FFA). All stimuli appeared pseudorandomly in a rectangular area with a visual angle of 6.4° in width and 4.6° in height.

Procedure

For the blocked-design runs in both experiment 1 and experiment 2 (Fig. 2b), participants were scanned for 2 runs with 20 s for each block. Twenty stimuli per block were visually presented, each for 250 ms with an inter-stimulus interval of 750 ms. All subjects performed a "right-left judgment" task, in which the center of each picture was slightly shifted from the fixation point, and participants were asked to make a judgment about whether the stimulus was to the right or the left relative to the fixation point.

For the event-related runs in experiment 1 (Fig. 2a), participants were scanned for 4 runs during which four kinds of stimuli and fixations were presented with the M-sequence (Buracas and Boynton 2002). Each stimulus was presented for 250 ms followed by 1750 ms of ISI. Each run consisted of 125 trials (25 for each stimulus type). Participants performed the same "right–left judgment" task as in the blocked-design runs.

Data acquisition

Experiment 1 was conducted on a 3T GE signa scanner and experiment 2 on a 3T Siemens Trio scanner. Functional images were acquired with an echo-planar imaging (EPI) sequence with standard parameters in experiment 1 (13 slices approximately parallel to the base of the temporal lobe, 4.0 mm slice thickness with no gap, field of view (FOV) = 220×220 mm^2, 64×64 matrix, voxel resolution = $3 \times 3 \times 4$ mm^3; TR = 2,000 ms for block-design scans, TR = 1,000 ms for event-related scans, TE = 35 ms, flip angle = 75°). In experiment 2, images were acquired at higher spatial resolution (13 slices approximately parallel to the base of the temporal lobe, 3.0 mm slice thickness with no gap, field of view (FOV) = 256×256 mm^2, 128×128 matrix, voxel resolution = $2 \times 2 \times 3$ mm^3, TR = 2,000 ms, TE = 35 ms, flip angle = 75°). For each subject, a T1-weighted anatomical volume (3D MPRAGE; $1 \times 1 \times 1$ mm^3 resolution) was acquired for localization and visualization of the functional data.

Data analysis

All data were analyzed with BrainVoyager software (brain innovation) and custom MATLAB codes.

General linear model analysis for experiment 1

Data were motion-corrected and smoothed with a Gaussian kernel of 4 mm FWHM for the block-design runs only. Statistic maps of the brain were computed by performing general linear model multiple regression tests, and ROIs were identified at individual level. There are 4 regressors

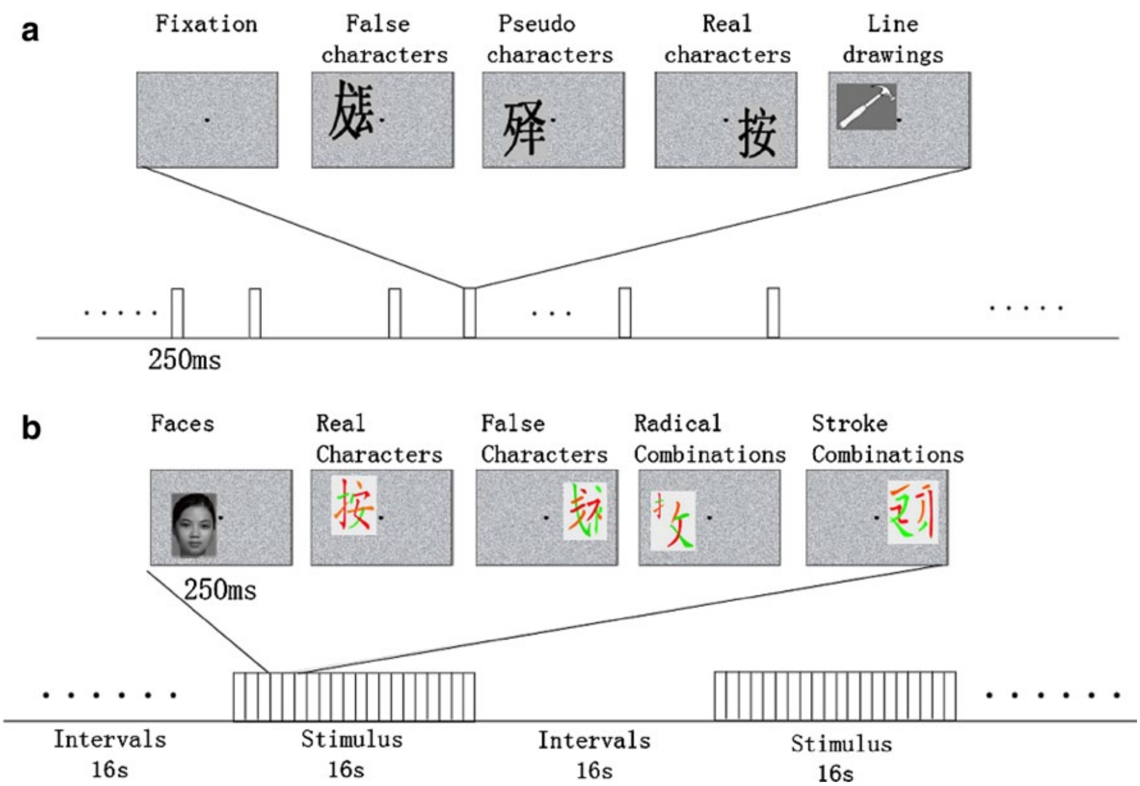

Fig. 2 Schematic depiction of the experimental paradigm. **a** Event-related runs in experiment 1. **b** Blocked-design runs in experiment 2

in the GLM model including fixation condition, and motion parameters were not added to the regressor models as the head motion was quite small. Significance maps of the brain were computed by performing *t* tests for pairwise comparisons of conditions ($p < 0.05$, FDR corrected for multiple comparisons).

The fusiform ROI corresponding to the presumed VWFA was defined as region in which Chinese characters generated higher activity than faces and line drawings. FFA in right hemisphere (rFFA) was defined as a region in which faces generated higher activity than Chinese characters. Event-related data in experiment 1 were motion-corrected, and then, time course data were extracted from the predefined VWFA ROI and rFFA. Statistical analysis was performed on the averaged responses from 6 to 12-s post-stimulus onset within each ROI.

Multi-voxel pattern analysis (MVPA) for experiment 2

Data from experiment 2 were used for multi-voxel pattern analysis (MVPA). Data were motion-corrected and unsmoothed spatially.

The ROIs for experiment 2 were defined based on both a functional localizer (same as in experiment 1) and anatomy: In each individual subject, the lateral part of left mid-fusiform was defined as a region in which Chinese characters generated higher activity than faces and line drawings (corresponding to the presumed VWFA). Once the VWFA was defined individually, the other two ROIs (center part and median part) in left mid-fusiform were defined on anatomical grounds according the position of VWFA, the three ROIs occupy the same position along the anterior–posterior axis, and together, they span a range of 40 mm in the lateral–medial direction. On the right side, we first identified the FFA (as a region in which faces generated higher activity than Chinese characters), which then determined the position of the ROIs along the anterior–posterior axis. At this location, the right mid-fusiform was further divided into the three ROIs (lateral part, center part, and median part) on anatomical grounds within a range of 40 mm in the lateral–medial direction, with the FFA roughly corresponding to the center part. The LOC was defined as a region in which line drawings generated higher activity than Chinese characters. V1 were defined as activated voxels along the calcarine sulcus.

We examined the spatial pattern of activation in the bilateral mid-fusiform ROIs (lateral, center, and median) as well as bilateral lateral occipital cortex (LOC) and the early visual cortex (V1). For all the predefined ROIs, we first calculated the average blood–oxygen-level dependent (BOLD) signals from each voxel between 8 and 12 s after stimulus onset of each block. Response amplitudes of individual voxels were then normalized relative to the average of the entire time course within each run to minimize baseline differences across runs. The resulting normalized activity patterns (for each block and for each ROI) were labeled according to their corresponding stimulus types (e.g., real characters, false characters, etc.) and served as input to the subsequent correlational analysis.

Cross-correlation was calculated between the fMRI signals of one test block and the template calculated from the samples of all other blocks. This template-test correlation was repeated for all blocks (leave-one-out). We used this procedure to avoid using the samples in the same block both for generating the template and the test as they are not independent data sets. We computed the correlation between the spatial patterns on the template-test sets from the same stimulus category (e.g., real characters–real characters) as well as from different stimulus categories (e.g., real characters–false characters). A higher correlation for the within-category spatial patterns than for between-category spatial patterns indicated the presence of category discriminative information in the spatial patterns in that ROI.

The correlation data could then be used to classify the stimulus into different categories. Essentially, for a given test stimulus, a higher within-category correlation than all between-category correlations would result in a correct classification of that stimulus type (a hit for the correctly classified category), while a higher between-category than within-category correlation would result in an incorrect classification (a false alarm for the incorrectly classified category).

Table 1 Talairach coordinates of VWFA and their respective cluster sizes for each observer

Subjects	*x*	*y*	*z*	Volume (mm^3)
1	−36	−59	−11	409
2	−44	−54	−12	801
3	−38	−59	0	680
4	−30	−41	−14	344
5	−34	−38	−21	205
6	−39	−60	−11	423
7	−33	−46	−20	385
8	−46	−50	−10	479
Mean	−38	−51	−12	466
SD	5	9	7	190

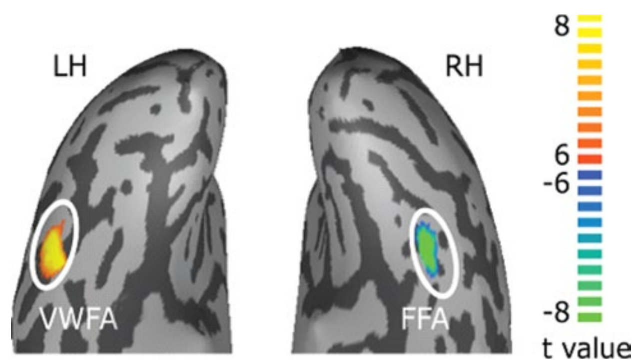

Fig. 3 Localizer results are displayed on a typical subject's ventral occipital-temporal cortical surface. Contrasting between characters and faces (line drawings) revealed a region in the lateral part of the left fusiform cortex with enhanced activation to Chinese characters ($p < 10^{-6}$, confirmed with Bonferroni correction, p(Bonf) < 0.05). This region is spatially consistent with the reported locations of the VWFA. A region with higher activity to faces than line drawings was revealed in the right fusiform cortex, corresponding to the FFA

Results

Orthographic sensitivity in VWFA examined by response magnitude

In the localizer scans, we identified a region in the lateral part of the left mid-fusiform gyrus (presumably VWFA, average Talairach coordinates: $x/y/z$: −38/−51/−12) with higher responses to Chinese characters than to both faces and line drawings in 8 of the 11 subjects (see Table 1). For the remaining 3 subjects, the same region can be found when contrasting Chinese characters with faces, but not with line drawings. Thus, only data from the first 8 subjects in whom we could robustly identify a VWFA were used in the response amplitude analysis. The VWFA and FFA are displayed on a typical subject's ventral occipital-temporal cortical surface (Fig. 3).

In the ROI corresponding to the VWFA, the false characters generated higher BOLD signal than both pseudo [$t(7) = 2.89$, $p = 0.023$] and real characters [$t(7) = 3.72$, $p = 0.007$] (Fig. 4). However, no significant difference was found between pseudo and real characters ($p > 0.1$). Although such a pattern of response was not seen in the medial part of the fusiform cortex (MFC), response to false characters was also higher than that of the real characters in the FFA on the right hemisphere (rFFA). Additionally, in none of the ROIs considered were responses to real characters different from that to pseudo characters (Fig. 4b). Therefore, these results suggest the possibility of orthographic sensitivity in VWFA, but the interpretation is weakened by the observation that some other areas also showed similar pattern of results. It is possible that orthographic sensitivity in VWFA is better reflected as variations in signal across voxels rather than changes in the mean BOLD signal averaged in the ROIs. Thus, we turn to the results of experiment 2.

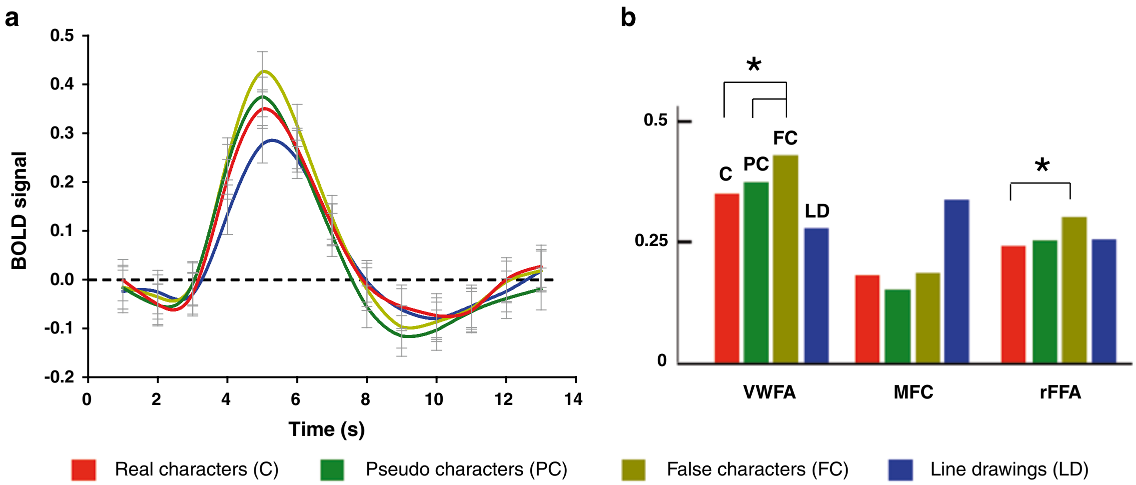

Fig. 4 Event-related responses to the three types of character-related stimuli and line drawings. **a** Time courses of BOLD responses to the four types of stimuli in VWFA. **b** Summary of response amplitudes in three ROIs. False characters had a higher signal than the real and pseudo characters in VWFA. The medial part of the left mid-fusiform cortex (MFC) showed much stronger responses to line drawings, consistent with results obtained in the block-designed experiment, but no difference between the three character-related stimuli. In the rFFA, false characters also had higher responses than real characters

Orthographic sensitivity in VWFA revealed by multi-voxel spatial pattern analysis

Classification performance based on comparing within and between-category spatial correlations is shown in Fig. 5 for each ROI. Faces are extremely well classified in multiple ROIs including the LOC, lateral, center, and median fusiform cortex of both hemispheres (left: $t = 5.68$, $p = 0.001$; $t = 10.8$, $p = 1 \times 10^{-5}$; $t = 6.48$, $p = 0.0003$; $t = 2.44$, $p = 0.044$; right: $t = 7.51$, $p = 0.0001$; $t = 18.73$, $p = 0$; $t = 7.52$, $p = 0.0001$; $t = 2.55$, $p = 0.038$), but not the early visual cortex. For faces, the classification performance in median mid-fusiform gyrus was significantly worse than in center and lateral mid-fusiform gyrus and in the LOC of both hemispheres [left: $t = 3.82$, $p = 0.007$; $t = 2.58$, $p = 0.037$; $t = 2.44$, $p = 0.045$; right: $t = 5.55$, $p = 0.001$; $t = 4.91$, $p = 0.002$; $t = 4.79$, $p = 0.002$; $F(7, 49) = 5.625$, $p = 8 \times 10^{-5}$]. The classification performances were not significantly different between LOC, lateral, and center mid-fusiform gyrus (all $p > 0.05$).

Among the character-related stimuli, radical combinations are well classified in the LOC (left: $t = 3.64$, $p = 0.008$; right: $t = 2.47$, $p = 0.043$) and in fusiform regions (including lateral, center, and median mid-fusiform) of both hemispheres (left: $t = 6.27$, $p = 0.0004$; $t = 4$, $p = 0.005$; $t = 2.538$, $p = 0.039$; right: $t = 3.34$, $p = 0.011$; $t = 9.347$, $p = 3 \times 10^{-5}$; $t = 2.54$, $p = 0.039$), with the best performance seen at the lateral part of the left fusiform gyrus and the central part of the right fusiform gyrus [$F(7, 49) = 3.171$, $p = 0.008$], and there is no significant difference between these two regions in their classification performances ($t = 0.574$, $p = 0.584$). However, there are a lot of "false positives" for radicals, with false characters particularly prone to be misclassified as radicals, such as in the lateral part of fusiform gyrus of both hemispheres (left: $t = 3.17$, $p = 0.016$; right: $t = 4.51$, $p = 0.003$) and in the central part of the right fusiform gyrus ($t = 2.60$, $p = 0.035$); even real characters were frequently misclassified as radicals in the median part of the right fusiform gyrus ($t = 2.55$, $p = 0.038$).

Real characters were classified well at the left lateral fusiform cortex (i.e., VWFA) ($t = 2.6$, $p = 0.036$) and bilateral LOC (left: $t = 3.35$, $p = 0.012$; right: $t = 2.8$, $p = 0.027$). The classification performance is not significantly different among these areas [$F(2, 14) = 0.2$, $p = 0.82$]. However, the pattern information is relatively localized in VWFA, with classification reduced to chance level in the central and median regions of the left fusiform gyrus (all $p > 0.05$). Real characters could not be classified correctly in right mid-fusiform gyrus (all $p > 0.05$) and were frequently misclassified as radicals in the median part of the right fusiform gyrus ($t = 2.55$, $p = 0.038$).

False characters were often misidentified as radicals, such as in the lateral part of the fusiform gyrus of both hemispheres (left: $t = 3.17$, $p = 0.016$; right: $t = 4.51$, $p = 0.003$) and in the center part of the right fusiform gyrus ($t = 2.6$, $p = 0.035$). False characters were equally likely to be correctly classified as false characters ($t = 2.66$, $p = 0.033$) and misclassified as radical combinations ($t = 3.17$, $p = 0.016$) in the lateral part of left mid-fusiform gyrus (VWFA).

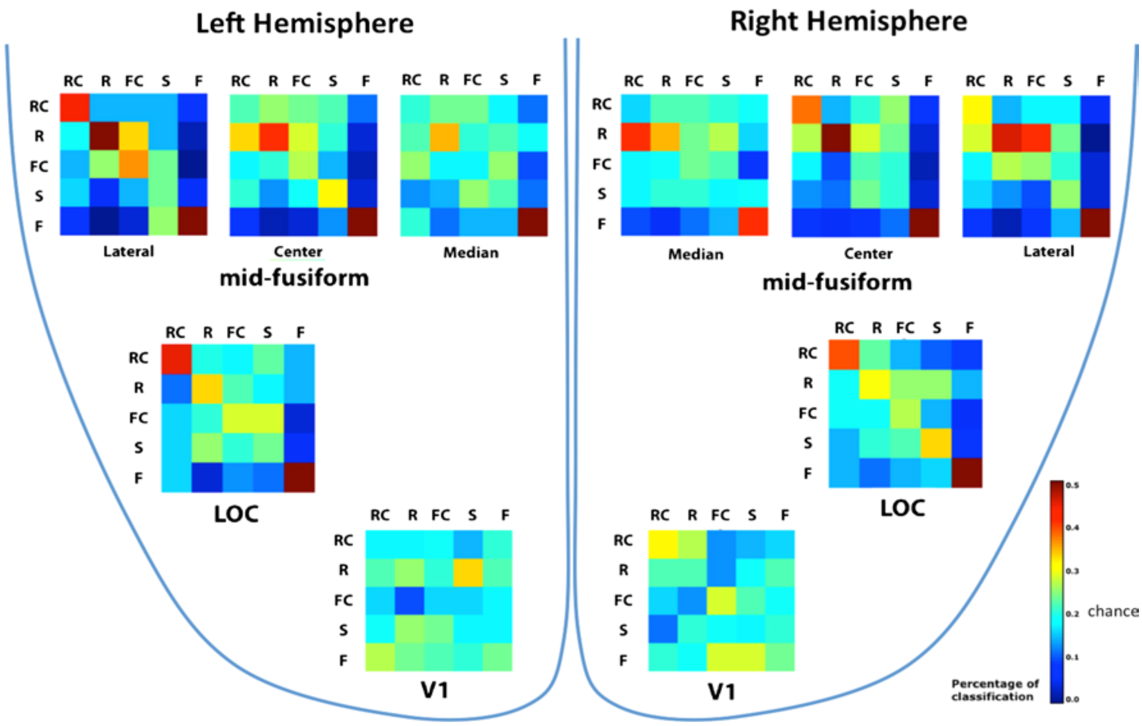

Fig. 5 Classification performance matrices based on correlation analysis across multiple voxels in pre-identified ROIs. *RC,* real characters; *R,* radicals; *FC,* false characters; *S,* strokes; and *F,* face. The horizontal axis is the test category and the vertical axis is the classified category. Faces are extremely well classified in all ROIs except *V1*, with in the median mid-fusiform significantly worse than in other regions. Radical combinations are well classified in all ROIs except *V1*, with the best performance seen at the lateral part of the left mid-fusiform gyrus and the central part of the right mid-fusiform gyrus. The best classification performance for real characters could be seen in the left lateral mid-fusiform region and both LOC. False characters were often misidentified as radicals, like in the lateral part of mid-fusiform gyrus of both hemisphere and in the center part of right mid-fusiform gyrus. False characters were equally likely to be correctly classified as false characters and be misclassified as radical combinations in VWFA. There was not a systematic spatial pattern for strokes, and their classification was largely random

Overall, there was not a systematic spatial pattern for strokes, and their classification was largely random. Interestingly, strokes were sometimes misclassified as radicals in the left early visual cortex ($t = 2.44$, $p = 0.045$) and misclassified as faces in the right V1 ($t = 2.60$, $p = 0.035$).

In order to understand more directly each region's ability to discriminate between pairs of stimuli, a discriminability index (DI), defined as the difference between the *z*-transforms of the hit rate and the false alarm rate, was calculated for specific pairs of character-like stimuli except the strokes in all ROIs.

For pairs between real characters and false characters, the left lateral mid-fusiform gyrus ($t = 6$, $p = 0.001$), the lateral ($t = 2.45$, $p = 0.044$) and central ($t = 3.393$, $p = 0.012$) part of the right mid-fusiform gyrus and both LOC (left: $t = 3.760$, $p = 0.007$; right: $t = 2.631$, $p = 0.034$) all showed significant discriminating performance. There is no significant difference among these areas in their ability in discriminating real characters and false characters [$F(4, 28) = 1.007$, $p = 0.42$]. Since false characters violate the spatial position rules of radicals in Chinese orthography, such orthographic information seems to be represented in the above described 5 areas.

For pairs between real characters and radical combinations, left lateral mid-fusiform gyrus ($t = 7.482$, $p = 0.0001$) and left LOC ($t = 6.495$, $p = 0.0003$) showed significantly above chance discrimination. The discriminating abilities of the lateral ($t = 2.190$, $p = 0.065$) and central ($t = 2.305$, $p = 0.055$) part of right mid-fusiform gyrus were marginal significant.

For pairs between radical combinations and false characters, the left lateral mid-fusiform gyrus ($t = 3.183$, $p = 0.015$) and the right LOC ($t = 5.076$, $p = 0.001$) showed significant discriminating ability, while discrimination at the central part of the right mid-fusiform gyrus ($t = 2.303$, $p = 0.055$) was marginal.

Taken together, the DI results show that (1) only left lateral mid-fusiform gyrus (VWFA) could significantly discriminate between the three character-related stimuli: real characters, radical combinations, and false characters. The discrimination between radical combinations and false characters is not as good as between real characters and radical combinations ($t = 2.353$, $p = 0.05$); (2) the distributed areas including the left lateral mid-fusiform gyrus (VWFA), the lateral and central part of the right mid-fusiform gyrus and both LOC, were sensitive to the legality of radical positions; (3) the right mid-fusifrom gyrus and both LOC have various degrees of discriminating ability, though not as comprehensive as the VWFA, between the three types of character-related stimuli: real characters, false characters, and radial combinations.

Discussion

In this study, we examined the amplitude of response and the spatial pattern of response to a number of character-related stimuli differing in lexical and orthographic properties. The results suggest that the ventral occipital-temporal cortex, especially the VWFA, is sensitive to Chinese characters' orthographic properties but lacks lexical sensitive. Importantly, the multiple voxel patterns in the VWFA generated the best classification performance for the three character-related stimuli (real characters, radical combinations, and false characters). The classification performance in the occipital-temporal cortex for character-related stimuli worsens as the stimuli violate more and more orthographic rules. Overall, our results suggest that both radical and radical position information is processed in the distributed lateral occipital to mid-fusiform areas, with orthographic sensitivity peaking at the VWFA.

The VWFA is involved in orthographic rather than lexical or phonological processing

Experiment 1 showed that fMRI response in the VWFA to false characters was significantly different than the responses to pseudo and real characters. This result suggests that the VWFA is sensitive to whether a character-like stimulus follows orthographic rules—because in both pseudo and real characters radicals are at their normal and legitimate positions, whereas in false characters, radicals are at positions that violate the regularity of Chinese orthography. This finding with Chinese characters is generally consistent with what have been suggested based on studies with alphabetic scripts that the VWFA is sensitive to orthographic information (Cohen et al. 2002; Vinckier et al. 2007; Glezer et al. 2009; Schurz et al. 2010; Braet et al. 2012), although there are still disputes on the level of orthographic complexity represented at the VWFA, for example, letter strings (e.g., Baker et al. 2007) or correct combinations of letter strings.

It is worth noting that the response amplitude of VWFA to pseudo characters was essentially the same as to real characters. As long as the stimuli conform to the orthographic rules, their lexical information does not modulate the response level at this area. This result is consistent with the idea that VWFA is sensitive to the stimulus' orthographic regularity (Cohen et al. 2002), but is not differentiating between the real words and the pseudo words (Vigneau et al. 2005). Related to and corroborating this point, in a recent ERP study, Lin et al. (2011) found that both pseudo and real characters produced left-lateralized N170 over the posterior occipitotemporal brain region, and the amplitude of the N170 response to both stimuli were the same.

It should be noted that Kronbichler et al. (2007) found a stronger response to pseudohomophones than real words in this region using a lexical decision task and Woollams et al. (2011) identified greater activation for pseudowords than words in the posterior LvOT cortex in a visual lexical decision task. These results reveal the difference between alphabetic and Chinese writing systems. With sound-based alphabetic scripts, it is possible that the observed effect is a mixed result of orthography and phonology processing, as both real and pseudo words could readily produce phonological activation as shown in some ERP studies (Bentin et al. 1999; Simon et al. 2006). In contrast, the logographic Chinese characters are thought to induce weaker activation of phonology (Chen and Shu 2001; Yeh and Li 2002). Another possible explanation for the discrepancy between these studies and ours is the differential influence of task demand (target detection in Vinckier's task and left–right judgment in ours). Interestingly, Wang et al. (2011) found that pseudo and real Chinese characters also produced a different degree of activation in VWFA. Again, task demand may be a key factor here, and it is likely that the use of one-back task in Wang et al's study induced a strong top–down modulation effect.

Orthography is represented in a distributed neural network in the occipitotemporal regions

The MVPA results of experiment 2 show that there are distinct neural patterns for processing different levels of Chinese orthography. Stroke combinations cannot be correctly classified in the ROIs we tested, and their classification was essentially random. Therefore, although psycholinguistic studies suggest strokes as a unit of Chinese orthography, there is no distinct pattern across voxels for processing this type of stimulus.

In contrast, the processing of false characters has a distinct corresponding pattern of response in a number of regions, and they are different from that of pseudo and real characters. Interestingly, false characters were easily misidentified as radical combinations in both lateral mid-fusiform gyrus and in the center of right mid-fusiform gyrus. This result makes sense when we consider their orthographic properties: the two radicals in a false character are in orthographically incorrect positions, which may prevent them from becoming a bound unit, making them similar to radical combinations. The fact that the lateral fusiform regions confuse radical combinations and false characters is a strong evidence for their sensitivity to the radical position, a key orthographic property of Chinese characters.

Radicals can be classified well in distributed areas, including lateral, center and median mid-fusiform gyrus, and the LOC, with the best in VWFA and in the center of right mid-fusiform gyrus. Compared to radicals, the pattern information related to real characters is more localized in the VWFA. These findings corroborate and extend the results of experiment 1. In experiment 1, we see character-related stimuli (real, pseudo, and false characters), all generated strong activation in the VWFA, while in experiment 2, MVPA results suggest that the category-specific information of real characters is more confined to the VWFA, while category-related information for false combinations of radicals is represented in more distributed areas, including the LOC and right fusiform regions. Our results are also in line with that of the most recent study by Braet et al. (2012), which also adopted MVPA technique. Although they found the VWFA has best classification performance for words, the LOC also seems to convey some orthographic information. Reading is one, albeit very specialized, perceptual task. From this perspective, the circuits for reading certainly should overlap with the neural circuits for general perceptual processing. It remains possible that the ventral occipitotemporal cortex's ability to discriminate between false and real characters is based on perceptual factors rather than orthographic properties. Such a consideration warrants further and more detailed research efforts. In conclusion, the present study demonstrated three important properties of the VWFA and neighboring regions. First, the VWFA is critically involved in processing orthographic information but is insensitive to lexical information. Second, radicals and combinations of radicals are likely represented in a distributed neural network with the VWFA containing the most specific information regarding a stimulus' orthographic regularity. Third, our results extend the earlier finding of a posterior to anterior progression of orthographic representation in the occipitotemporal cortex (Vinckier et al. 2007) by showing the specific orthographic properties represented at the bilateral LOC and mid-fusiform regions.

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