The Representations of Chinese Characters: Evidence from Sublexical Components

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Little research has been done about the neural substrate of the sublexical level of Chinese word recognition. In particular, it is unclear how radicals participate in Chinese word processing. We compared two measures of radical combinability, position-general radical combinability (GRC) and position-specific radical combinability (SRC) depending on whether the position of the radical is taken into account. We selected characters with embedded target radicals that had different GRC and SRC measures. These measures were used as predictors in a parametric modulation analysis and a multivariate representational similarity analysis. Human participants with native Mandarin speakers (17 males and 24 females) were asked to read words in search of animal words. Results showed that SRC is a better predictor than GRC in decoding the neural patterns. Whole-brain analysis indicated that SRC is encoded bilaterally in the inferior frontal gyrus (IFG, pars opercularis, and pars triangularis), the middle frontal gyrus (MFG), and a region on the border of the superior parietal lobule and the inferior parietal lobule (SPL/IPL). Region-of-interest-based RSA confirmed the results of the whole-brain analysis. Furthermore, we observed a correlation of another sublexical variable, logographeme composition, with bilateral activity in SPL. Logographemes refer to the basic stroke combinations that form radicals and characters. Finally, we observed involvement of bilateral cerebellum activity in Chinese word recognition. Our findings confirm the importance of sublexical components (SRC and logographeme composition) in Chinese word recognition and also confirm that Chinese word recognition involves more bilateral processing than word recognition in alphabetical languages.

Key words: Chinese word recognition; radical combinability; RSA; sublexical

Significance Statement

Chinese is a logographic language. However, characters contain informative subword components (radicals, logographemes, and strokes). We investigated whether the position of the radical is important. We presented carefully selected words and looked where brain activity correlated with subword information. Results indicate that position-dependent radicals predict brain encoding in a network of regions associated with Chinese word recognition, including higher order regions such as bilateral IFG, MFG, and SPL/IPL. Logographeme composition had an effect as well. Our findings provide strong evidence (1) for the importance of position-specific radical information and logographemes in Chinese word recognition, (2) that current brain imaging techniques are best suited to study these, and (3) that confirms the interactive nature of Chinese character recognition.

Introduction

Exploring the neural basis of visual word processing is a central issue in neuroscientific research. In alphabetic languages, the ventral occipitotemporal (vOT) cortex was found to connect information from the primary visual cortex to language processing areas via two main routes, one dorsal and one ventral (Carreiras et al., 2014). However, neural patterns involved in logographic scripts (like Chinese) are different from those of alphabetic words (Tan et al., 2005). The dorsal route connecting vOT with the inferior frontal cortex includes a region on the border of the superior and inferior parietal lobule instead of the angular gyrus (Tan et al., 2005), and right-hemisphere language regions are more active in encoding Chinese characters (Zhao et al., 2017). These activation differences can be explained by several factors. One is the orthographic structure of Chinese characters. Another is that Chinese characters refer primarily to morphemes, not phonemes (Tan and Perfetti, 1998). Although...
numerous studies have investigated the neural mechanisms of Chinese characters (Wu et al., 2012), there is little knowledge about the relation between Chinese characters and their sublexical components.

Like alphabetic words, Chinese words often contain subword information that may be informative. For instance, polymorphemic Chinese characters usually include useful subword information about word meaning (黑 (grandson) → 子 (son) 小 (little)), similar to English words like basketball. These properties of Chinese characters can be used to obtain deeper insight in the neural substrate of word processing, just like they are used in alphabetic languages (Forgács et al., 2012). The Chinese language may even be better suited for this type of analysis, given the structure of Chinese words.

The functional orthographic unit of Chinese words is the radical (Chen et al., 1996). A character is composed of one or more radicals, which can be situated on the left, right, bottom, or top (Taft and Zhu, 1997). The radicals frequently contain functional information related to the word denoted by the character, as indicated above. More than 80% of 7000 frequent characters contain radicals carrying probabilistic indications about pronunciation or meaning of words (Li and Kang, 1993). The relation between the radical and the full word can be used to obtain further insight into brain processes involved in Chinese word recognition. For instance, Liu et al. (2020) found extra activation in the posterior fusiform gyrus of the hemisphere contralateral to the phonetic radical position, in line with predictions from the split-fovea hypothesis (Ellis and Brysbaert, 2010).

In the present study, we examined the relationship between the radical and the character by adopting another variable, radical combinability, which refers to the number of combinations a radical can have to form characters (Feldman and Siok, 1997). For example, the radical 黑 forms a word on its own but is also a radical in 15 other characters, where it can appear on the left, right, top, or bottom (e.g., 黒, 黑, 黒, 黒). Because of the various positions in which radicals can appear, there are two ways that radical combinability can be calculated, namely, one in which the position of the radical is disregarded and one in which the position is included (Wu et al., 2015). The radical 黑 appears in 16 words (15 compound characters and 1 character containing the radical only). So the position-general radical combinability (GRC) of 黒 is 16. Of these words, 黒 appears 11 times in the left half of characters. So the position-specific radical combinability (SRC) of 黒 in the left part is 11. The SRC of radical 黒 on the right is 1, at the top it is 1, and at the bottom it is 2. Both combinability measures are frequency measures (number of characters containing the radical).

To deepen our understanding of the neural substrates of Chinese words, we varied GRC and SRC to examine which measure best predicts differences in brain activation and where these differences are situated.

Materials and Methods

Power considerations. The power of studies in which multiple stimuli are presented to participants depends on both the number of participants and the number of stimuli presented per condition (Lorch and Myers, 1990; Neu, 2019). Westfall et al. (2014) calculated that 40 participants and 40 stimuli per condition is a good starting point for effect sizes of $d = 0.4$. We included the recommended number of participants but increased the number of trials to 160, so that correlations were measured with an $SE$ of $r = 0.08$ per participant.

Participants. Forty-one healthy graduate students (17 males; mean age, 26.8 years; range, 23–34 years) were paid 25 Euros to take part in the experiment. All participants were native literate Mandarin speakers with normal or corrected-to-normal vision, right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), and had no history of neurologic or psychiatric problems. All participants were studying at Ghent University and screened to meet all conditions for scanning. The study was approved by the Ethics Committee of Ghent University Hospital. Before the experiment, participants signed an informed consent form. The same participant group took part in the Liu et al. (2020) study. The experiments formed separate runs, with the Liu et al. (2020) task (a color search task) presented after the present one.

Materials. We selected 80 target radicals with a wide range of radical combinability values. The radical combinability value for each radical was calculated on the basis of the International Organization for Standardization 10.4.6 database (https://glyphs.iso10646hkn.ccs.cjjsp.lang=en_US). As indicated above, two types of radical combinability were counted. For a particular radical, like 黒, we ascertained the GRC and the SRC.

The target radicals were part of 80 characters, which contained two radicals in a left-right structure. This is the dominant configuration of Chinese characters (Hsiao and Shillcock, 2006) and simplifies the calculation of the stimulus characteristics. Half of the target radicals were in the left half, half in the right. It is further worth repeating that all target radicals also existed as words with high frequency.

We decided on the basis of the fact that the logographic Chinese script has a hierarchical structure, including characters, radicals, logographs, and strokes, which may all be important for word recognition. For the character and radical level, we took into account the frequency of the character (CF) and the frequency of the radical (CFR) as an independent word (Cai and Brysbaert, 2010). The logographic level refers to basic stroke combinations that form radicals and characters. This is a level lower than the radical and has been proposed by some authors as the basic unit of Chinese characters (Han et al., 2007; Law and Leung, 2000). For example, the stimuli character 静 (quiet) contains four logographs 黙 月 早 仏, the character 肮 (dirty) contains three logographs 月 广 土. We looked at the logographeme composition and the number of graphemes shared in the words presented (see below, ROI-based RSA). For the stroke level we included the number of strokes in the character (NSC) and the number of strokes in the target radical (NSR).

In addition to the characteristics of the characters and the target radicals, we also measured the characteristics of the non-target radicals. Given that these were not manipulated, we expected them to be independent of GRC or SRC of the target radicals. Still, we calculated them to be sure.

To decide on control variables, we started from the fact that the logographic Chinese script has a hierarchical structure, including characters, radicals, logographs, and strokes, which may all be important for word recognition. For the character and radical level, we took into account the frequency of the character (CF) and the frequency of the radical (CFR) as an independent word (Cai and Brysbaert, 2010). The logographic level refers to basic stroke combinations that form radicals and characters. This is a level lower than the radical and has been proposed by some authors as the basic unit of Chinese characters (Han et al., 2007; Law and Leung, 2000). For example, the stimuli character 静 (quiet) contains four logographs 黙 月 早 仏, the character 肮 (dirty) contains three logographs 月 广 土. We looked at the logographeme composition and the number of graphemes shared in the words presented (see below, ROI-based RSA). For the stroke level we included the number of strokes in the character (NSC) and the number of strokes in the target radical (NSR).

In addition to the characteristics of the characters and the target radicals, we also measured the characteristics of the non-target radicals. Given that these were not manipulated, we expected them to be independent of GRC or SRC of the target radicals. Still, we calculated them to be sure.
Before entering the scanner, each participant underwent a practice session. After the participants fully understood the task requirements and were able to complete the practice session correctly, they were allowed to perform the task in the scanner. The paradigm performed during practice was the same as the experimental paradigm in the scanner, but different items were used during practice.

fMRI data acquisition and preprocessing. Images were acquired using a 3T Siemens Magnetom Prisma scanner with a 64-channel radio frequency head coil located at Ghent University. Visual stimuli were presented using PsychoPy2 software (Peirce et al., 2019) and projected onto a translucent screen at the end of the scanner. Participants viewed the stimuli via a mirror fixed on the head coil in front of their eyes. High-resolution T1-weighted 3D structural images were first obtained by using an MP-RAGE sequence [repetition time (TR) = 2250 ms, echo time (TE) = 4.18 ms, field of view (FOV) = 256 mm, flip angle = 9°, slice thickness = 1 mm, distance factor = 50%, voxel size = 1 × 1 × 1 mm³, 176 slices]. Then whole-brain functional images were recorded by the multiband-accelerated echoplanar imaging (EPI) sequence (TR = 1000 ms, TE = 31 ms, FOV = 210 mm, flip angle = 52°, slice thickness = 2.5 mm, distance factor = 0%, voxel size = 2.5 × 2.5 × 2.5 mm³, 56 slices, multiband factor = 4). In addition, a gradient echo field map (TR = 548 ms, TE1 = 4.92 ms, TE2 = 7.38 ms, slice thickness = 2.5 mm) was collected for each participant.

The preprocessing was conducted using SPM12 software (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) in MATLAB 2016b (MathWorks). For the multivariate tests, the preprocessing procedure included spatial realignment and unwarping using a field mapping and slice timing correction. For the univariate analysis, the corrected EPI images were coregistered to high-resolution anatomic images, normalized to the MNI T1 template (2 mm isotropic voxels) and spatially smoothed with a 6 mm FWHM Gaussian kernel. The preprocessed data files are available at https://osf.io/krdze/view_only=9b16db9134c74bb99145e62f2994d361.

Univariate parametric modulation analysis. To investigate the contribution of the sublexical level to the neural substrates underlying Chinese word processing, we estimated the modulation of the radical combinatoriality on brain activity by performing a voxelwise parametric modulation analysis (Büchel et al., 1998). The analysis involved, at the participant level, two parametric regressors (SRC and GRC) on correct trials. By using the general linear model, both parametric regressors were convolved with the canonical hemodynamic response function (HRF; Friston et al., 1994) in the design matrices.

Given the correlation between target radical SRC and GRC (Table 1), we estimated two separate models. In the first one, SRC was set as the modulation parameter, and GRC was defined as a covariate. For the second, GRC was set as the modulation parameter, and SRC was used as covariate. For both models, six head motion parameters were added to the design matrix as regressors of no interest, and the baseline drifts were removed by a temporal high-pass filter (cutoff at 128 s).

To bring the participant analyses to the group level, we ran one-sample t-tests to determine which brain regions were significantly activated in each model, with the subjects treated as the random effects. The group statistical map was familywise error (FWE) corrected for multiple comparisons with a cluster-level threshold of p < 0.05, corresponding to a primary voxel-level threshold of p < 0.001 (k ≥ 154 voxels). By doing so, we could find which regions’ activations show a monotonic modulation by SRC or GRC.

Multivariate representational similarity analysis. A multivariate RSA (Kriegeskorte et al., 2008a) was run to evaluate how the sublexical features of Chinese characters map onto neural patterns. In this analysis, the preprocessed data without smoothing or normalization was used. For each participant, we modeled each trial as a separate regressor, convoluted with the canonical HRF (Friston et al., 1994) with a high-pass filter (cutoff at 128 s) through a general linear model, to estimate the brain’s response (β maps) to the target Chinese characters. The head motion parameters were also modeled as nuisance variables in the design matrix. Then the mean β maps of the individual characters were created by averaging the repeated items over the 2 runs. One RSA connectivity pattern was generated for each participant. The subsequent RSA analysis used a whole-brain searchlight algorithm (Kriegeskorte et al., 2006).
and ROI-based was performed with the Decoding Toolbox (Hebart et al., 2015).

**Whole-brain searchlight RSA.** In this analysis, we implemented RSA to examine the effect of the two radical combinability measures on the neural representations across the whole-brain. To do so, first we constructed two representational dissimilarity matrices (RDMs) as the predicted models based on SRC and GRC of the target radicals (Fig. 2B). For example, the predicted RDM of SRC was constructed to reflect the dissimilarity of the position-dependent radical combinability of the target character to the other characters. Dissimilarity was calculated for each pair of characters. Specifically, the dissimilarity value of a single character pair was calculated as 1 minus the ratio of the SRC difference between this pair of items. As a result, a stimulus-pair with similar SRCs is expected to be close to 0, whereas dissimilar stimulus-pair are close to

![Figure 2](image.png)

**Figure 2.** The procedure of RSA. **A,** The searchlight RSA approach was performed by extracting the neural RDM (Person’s correlation) from each sphere with a four-voxel radius and then correlating them with two main predicted RDMs (SRC and GRC) using Spearman’s correlation. By doing so, we could get a correlation coefficient map for each model. **B,** Predicted models used in the searchlight RSA. The RDMs were established to indicate the variables of the radical combinability with (SRC) or without (GRC) position information. **C,** Predicted models additionally used in the ROI-based RSA approach. These RDMs were built to indicate the control variables. These include the logographeme overlap, the number of strokes of the whole character (NSC) and the target radical (NSR), the position of the target radical, and the visual pixel information.

<table>
<thead>
<tr>
<th>SRC</th>
<th>GRC</th>
<th>Logo</th>
<th>NSC</th>
<th>NSR</th>
<th>Position</th>
<th>Pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.236***</td>
<td>0.011</td>
<td>0.007</td>
<td>0.011</td>
<td>0.056*</td>
<td>−0.039</td>
</tr>
<tr>
<td>GRC</td>
<td>1</td>
<td>0.039</td>
<td>0.098***</td>
<td>0.057*</td>
<td>0.008</td>
<td>0.013</td>
</tr>
<tr>
<td>Logo</td>
<td>1</td>
<td>0.129***</td>
<td>0.124***</td>
<td>−0.008</td>
<td>0.194***</td>
<td></td>
</tr>
<tr>
<td>NSC</td>
<td>1</td>
<td>0.366***</td>
<td>0.053</td>
<td>0.138***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSR</td>
<td>1</td>
<td>0.006</td>
<td>0.017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>1</td>
<td>0.0464</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixel</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Logo, Logographeme. Bonferroni’s correction was used for multiple comparisons. *p < 0.05, ***p < 0.001.
1, resulting in an 80 × 80 symmetry matrix. A similar predicted RDM was calculated for GRC.

Second, RDMs of neural activity were created within a spherical searchlight of a four-voxel radius for each participant. Specifically, the trial-specific response patterns (β maps) were extracted to calculate the correlation distances by 1 minus the Pearson’s correlation value between response patterns of each pair of trials, which also resulted in an 80 × 80 symmetry matrix (Fig. 2A). Next, the neural RDMs were correlated with the two predictor RDMs (Spearman’s rank correlation). Only the unique off-diagonal values of RDMs were used to avoid inflated positive results (Ritchie et al., 2017). Fisher z transformed coefficients were assigned to the central voxel of the searchlight sphere. The similarity computation was iterated across the whole-brain so that two correlation coefficients maps were obtained for each participant, reflecting how each predictor model explained brain activity. We performed normalization and smoothing as in the univariate analysis.

Statistical significance was assessed by both parametrically one sample t tests based on the random-effects model and the permutation-based nonparametric statistical tests proposed by Stelzer et al. (2013). For the former analysis, the group statistical map to the SRC or GRC model was familywise error (FWE) corrected for multiple comparisons with a cluster-level threshold of p < 0.05, corresponding to a primary voxel-level threshold of p < 0.001 (k ≥ 56 voxels). The latter analysis is more complex. On the first level, the neural response patterns of the trial were permuted 100 times by randomly shifting the character labels and repeating the searchlight procedure as above to obtain 100 permuted coefficients maps for each participant. On the group level, we randomly sampled one of the permuted coefficient maps of each participant 50,000 times and averaged them to create 50,000 permuted group maps, which were used to construct a null distribution for each voxel. A voxelwise threshold map could then be established by extracting the corresponding coefficients for which the right-tailed area of the null distribution of each voxel was below 0.001 (i.e., p < 0.001). We used this voxelwise threshold map to threshold the original (nonpermuted) group maps. In addition, 50,000 permuted group maps were also thresholded, and all connected voxels (i.e., a cluster) with values exceeding the threshold were selected to build a null distribution of cluster sizes. By this, we can calculate the p value for all surviving clusters from the thresholded original group maps. For the final statistics, the p value (at p < 0.05) with FWE-corrected at cluster level was adopted to find the significant clusters or regions.

ROI-based RSA. From the existing literature, we identified the brain regions likely to be implicated in representing radical combinability (the same regions as used in Liu et al., 2020). Then an ROI-based analysis was conducted in these predefined areas to reveal the finer representation of each variable, also taking into account the multilayer orthographic control variables (Fig. 2C). These control variables were not included in the whole-brain analysis because in the present study we were mainly interested in how the radical, the functional orthographic control variables (predictors to make sure our conclusions were not contaminated by other variables. Because the multilayer orthographic structure of Chinese characters is an unavoidable property in the study of Chinese word representation, it is important to consider all layers of the Chinese word structure (Fig. 2B,C) and evaluate the extent to which each modeled variable explained the neural encoding in each identified brain region.

To the low-level visual perception of Chinese words, we calculated four predicted models, which respectively were predicted RDMs of the number of strokes of the whole character (NSC) and the target radical (NSR), the position of the target radical, and visual pixel information. For instance, the predicted RDM of NSC was constructed to reflect the NSC distance between each character pair of the stimulus set. To a single word pair, the dissimilarity was calculated by one minus the ratio of NSC between words. The same procedure was used to calculate the predicted RDM of NSR. The predicted RDM of the target radical position was built with zero representing the same position and one referring to the different positions. Finally, the predicted RDM of word pixels was measured by using a binary silhouette of each character and computing the pixelwise nonoverlap portion of the two images (Kriegeskorte et al., 2008b; Fischer-Baum et al., 2017).

The predicted RDM of logographemes was defined to reflect the overlap in logographemes in word pairs. For a single pair of the stimulus set, the dissimilarity value was calculated by one minus the number of logographemes shared among the word pair while ignoring their position information relative to the total number of logographemes in these two words. For example, the stimulus character 靜 (quiet) contains four logographemes [¥, 月, 广, ヨ], the character 肮 (dirty) contains three logographemes [¥, 广, 土], and there is one logographeme shared by both characters [月]. Therefore, the dissimilarity of this word pair would be 1–2/7.

The correlations among the various predicted RDMs are shown in Table 2. The correlations are low enough to not cause problems of multicollinearity in multiple regression analysis.

The ROIs were defined mainly according to a meta-analysis by Wu et al. (2012), which focused on the neural networks underlying the orthographic, phonological, and semantic processing of Chinese words. For orthography, they found the cortical areas were mainly activated in the left hemisphere, including the middle occipital gyrus (MOG), the middle part of the fusiform gyrus (FG), the superior parietal lobule (SPL), and the middle frontal gyrus (MFG). The ROIs were defined in the MNI standard space of the left hemisphere as boxes centered on the

Table 3. Univariate brain activities for the SRC model with the location and coordinates of peak activation

<table>
<thead>
<tr>
<th>Region</th>
<th>Side</th>
<th>MNI coordinates</th>
<th>Cluster size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle frontal gyrus</td>
<td>L</td>
<td>−44 10  28</td>
<td>5.66 1283</td>
</tr>
<tr>
<td>Inferior frontal gyrus, triangular part</td>
<td></td>
<td>−28 −66 46</td>
<td>4.89 430</td>
</tr>
<tr>
<td>Inferior frontal gyrus, opercular part</td>
<td></td>
<td>−24 44 46</td>
<td>4.67 303</td>
</tr>
<tr>
<td>Superior parietal lobule</td>
<td></td>
<td>−46 −54 −12</td>
<td>4.67 303</td>
</tr>
<tr>
<td>Cerebellum posterior lobe</td>
<td></td>
<td>0 −68 −24</td>
<td>5.33 426</td>
</tr>
<tr>
<td>Superior frontal gyrus</td>
<td></td>
<td>38 16 4</td>
<td>4.59 256</td>
</tr>
<tr>
<td>Cerebellum VI</td>
<td>R</td>
<td>32 10 30</td>
<td>3.85 215</td>
</tr>
</tbody>
</table>

Clusterwise, p < 0.05, FWE corrected.

Figure 3. Whole-brain group-level activation modulated by the parameter regressor of SRC, the statistical map was thresholded at clusterwise FWE < 0.05. R, Right hemisphere (Table 3).
peak coordinates defined by Wu et al. (2012). Specifically, MOG ranged from \( x = -35 \) to \(-10, y = -90 \) to \(-70, z = 14\) to \(-29\); FG ranged from \( x = -54 \) to \(-34, y = -70 \) to \(-45, z = -20 \) to \(-5\); SPL ranged from \( x = -40 \) to \(-20, y = -73 \) to \(-48, z = 44\) to \(-59\); and MFG ranged from \( x = -54 \) to \(-34, y = 5\) to \(-30, z = 27\) to \(-42\). The FG mask was centered slightly posterior to the peak coordinate given by Wu et al. (2012) to cover the brain regions defined as the visual word form area (the vOT) in other studies (Twoomey et al., 2011; Zhao et al., 2017).

In addition to the above four ROIs, we added the anatomically defined inferior frontal gyrus (IFG) consisting of the pars opercularis (Brodmann area 44) and pars triangularis (Brodmann area 45) in the automated anatomical labeling atlas (Tzourio-Mazoyer et al., 2002), excluding the overlap with the predefined MFG. As Wu et al. (2012) also reported involvement of the cerebellum in the left cerebellum lobule VI, we added the cerebellum as another ROI. Because we had no specific predictions of which part would be involved, we used the whole cerebellum. Finally, we added the posterior part of the fusiform gyrus (postFG) as ROI, defined as \( x = -54 \) to \(-34, y = -90 \) to \(-70, z = -20 \) to \(-5\). In our previous research (Liu et al., 2020), we found an effect of phonology in this area. Notably, because the ROIs were defined with different methods, the interpretation of their volumes may differ slightly. Then all of predefined ROIs were projected to the native space of the participants.

To consider the engagement of the right hemisphere in reading Chinese words (Zhao et al., 2017), we further selected the mirror reversed masks in the right hemisphere as ROIs. Within each ROI, the neural RDM was calculated for each participant. Considering that the predictor models were not orthogonal to each other, and to determine the exact influence of the variables, in each ROI we ran multiple regression analysis by using a linear mixed-effect model (lme4 1.1 package) and random factor (subject), then the likelihood ratio test was used to determine the performance of each model. Considering there were multiple ROIs and variables, Bonferroni’s correction was used to counteract the issue of multiple comparisons.

**Results**

**Behavioral results**

No participant reported difficulty in completing the animal word searching task, and participants made on average 0.5% errors. Importantly, the number of button presses to the critical stimuli was less than one per participant. Considering the minimal impact of the participant’s response, the few critical stimuli with button presses were omitted from the univariate analyses while keeping all the critical stimuli for the RSA approach so that the dimension of the neural RDM is equal for each participant.

**Univariate analysis results**

The parametric modulation analysis was run to estimate the extent to which the radical combinability measures correlated with changes in neural activity in various brain regions. As indicated above, we used two measures, depending on whether the position of the radical was taken into account or not. To do so, we established two models; in one model, the SRC was set as the modulation parameter and GRC as a covariate and in the other model, SRC was set as the modulation parameter and SRC as covariate.

The group whole-brain analysis showed that SRC was a much better predictor of changes in the BOLD signal than GRC (Fig. 3; Table 3). Brain activity was correlated with SRC in a broad network especially in the left hemisphere. It included MFG and IFG, the superior frontal gyrus, a region on the border of the SPL and inferior parietal lobule (IPL), and FG (or vOT). Interestingly, there was also clear evidence for a contribution of the left cerebellum. Some regions located in the right hemisphere were also involved, like the insula, homolog regions to IFG, MFG in the frontal lobe, and the cerebellum (Fig. 3; Table 3).

**Table 4. Significant correlated regions in RSA searchlight predicted by the SRC model**

<table>
<thead>
<tr>
<th>Region</th>
<th>Side</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Peak z</th>
<th>Cluster size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle frontal gyrus</td>
<td>L</td>
<td>-15</td>
<td>35</td>
<td>26</td>
<td>4.59</td>
<td>56</td>
</tr>
<tr>
<td>Precentral</td>
<td>L</td>
<td>-15</td>
<td>-49</td>
<td>26</td>
<td>4.10</td>
<td>240</td>
</tr>
<tr>
<td>Cerebelum posterior lobe</td>
<td>L</td>
<td>-27</td>
<td>-67</td>
<td>-52</td>
<td>3.89</td>
<td>226</td>
</tr>
<tr>
<td>Inferior frontal gyrus, triangular part</td>
<td>R</td>
<td>27</td>
<td>26</td>
<td>20</td>
<td>4.89</td>
<td>124</td>
</tr>
<tr>
<td>Frontal lobe</td>
<td>R</td>
<td>27</td>
<td>-28</td>
<td>32</td>
<td>4.74</td>
<td>137</td>
</tr>
<tr>
<td>Cerebelum VI</td>
<td>R</td>
<td>15</td>
<td>-67</td>
<td>-19</td>
<td>3.83</td>
<td>59</td>
</tr>
</tbody>
</table>

One-sample t test was adopted (clusterwise, \( p < 0.05; \) FWE corrected).
In contrast to the SRC results, there were no brain regions showing an association between signal intensity and GRC values beyond the effects of SRC, even when we adopted a liberal threshold (p < 0.001, uncorrected).

**Multivoxel RSA results**

*Searchlight RSA results of the radical combinability*

To further decode the representation patterns of the radical combinability, we also calculated RSA (Kriegeskorte et al., 2008a) with the whole-brain searchlight approach (Kriegeskorte et al., 2006). The neural RDMs were compared with the activation patterns predicted by RDMs coding for SRC or GRC. We used both parametrical t tests and nonparametric, permutation-based statistical tests to estimate significance. The results were almost the same for both techniques (Fig. 4).

In line with the univariate analysis, GRC did not correlate with brain activity. In contrast, the SRC model correlated significantly with neural activity. For the t test analysis this was true in left MFG, precuneus, cerebellum, and right IFG (pars triangularis), frontal lobe, and cerebellum (Fig. 4A; Table 4).

Very much the same regions correlated significantly in the permutation-based test, but there was evidence for a stronger right-hemisphere contribution (Fig. 4B). The main contributing areas in the right hemisphere were IFG (pars opercularis and pars triangularis), MFG, precuneus, IPL, cingulate gyrus (peak MNI: 32, −54, −50, k = 17,600), and the cerebellum posterior lobe. In the left hemisphere, the significant clusters were the IFG (including pars triangularis), MFG, insula, anterior cingulate, medial frontal gyrus, superior frontal gyrus, and putamen (peak MNI: −18, 22, −10, k = 3691).

**ROI-based RSA results of the multilayer orthographic variables of characters**

So far, we have looked at whole-brain data (both univariate and multivariate). This is important not to overlook important contributions of brain regions to the processing of radical combinability. However, because of the multiple comparison correction, we may be missing interesting patterns in specific regions of interest.

To estimate the fine-grained representation of each orthographic layer and examine the extent to which they contributed to the activity in specific regions, we ran extra analyses based on the predefined ROIs defined above. For each ROI, the participant’s neural RDMs were extracted and correlated with the predictor models on the basis of multiple mixed-effect regression analysis (Table 5; Fig. 5).

The analyses revealed that SRC was encoded bilaterally in MFG and IFG, which was consistent with the whole-brain analyses (Figs. 3, 4). Further in line with whole-brain analyses is the absence of a genuine effect of GRC in all ROIs tested (except the left FG). This further confirms the superiority of SRC to GRC. Another expected finding was the effect of the number of character strokes (NSC) in FG, more so in the left hemisphere than in the right hemisphere. We did not find significant correlations in posIFG and MOG with any of the variables we used.

An interesting new finding was the correlation between the logographeme model and neural activity in SPL bilaterally. There were also correlations between the logographeme model and neural activity in left MFG and IFG. This suggests that this sublexical variable is more useful to include in future studies than GRC.

A second interesting new finding was the involvement of the cerebellum in sublexical Chinese word processing. Indeed, activity in this brain region correlated with both the SRC and the logographeme models. The former was particularly clear in the left cerebellum, whereas the latter was stronger in the right cerebellum.

**Discussion**

In this study we explored the brain regions involved in Chinese character recognition. Specifically, we examined correlations of two measures of radical combinability with brain activity in different regions. This allowed us to address the following questions: (1) which brain regions are involved, and (2) which measure of radical combinability is the most informative?

Our findings indicate that SRC is a better measure than GRC. Radical combinability refers to the number of Chinese words a radical appears in. Taft and Zhu (1997) noticed that participants...
recognized Chinese characters faster if the characters included radicals appearing in many other characters than if radicals were rather rare. The measure they used was a GRC measure. They simply counted the number of Chinese characters in which the radical appeared. The possibility that this may have been suboptimal could be seen in the observation that the effects were not completely the same for radicals in the left half of Chinese characters and radicals in the right half.

Several authors have questioned the correctness of the position-independent GRC measure (Su et al., 2012). Wu et al. (2015), for instance, wondered whether an SRC measure would not be better. In two ERP studies they concluded that radical position plays an important role in Chinese character reading, which influences not only the sublexical orthographic processing but also the character semantic activation.

The present study continued this line of research and compared the usefulness of GRC and SRC in an fMRI study. Our findings were surprisingly clear. If SRC was used as main predictor, a network of brain regions correlated with the variable, which largely overlapped with the network of regions reported in meta-analyses of Chinese word recognition (Wu et al., 2012). In contrast, GRC did not correlate with activity in any expected region once SRC was entered as a covariate. This suggests that SRC is a better measure of radical combinability in Chinese character recognition than GRC.

Our findings further confirm the strong involvement of MFG and IFG in Chinese character recognition. In a meta-analysis, Tan et al. (2005) reported a larger involvement of MFG in Chinese word recognition than in English word recognition, which they attributed to the greater role of word-based (addressed) phonology in logographic languages than in alphabetical languages. The rapid involvement of the frontal cortex in visual word recognition has been documented before (Woodhead et al., 2014) but has mainly been ascribed to letter-based (assembled) phonology. Our data suggest that this is not the full story. Indeed, Hagoort (2017) stressed the importance of dynamic interactions between temporoparietal areas and frontal cortex for the semantic interpretation of linguistic utterances. Our semantic animal search task may have accentuated these interactions. Research of Chinese word recognition indicates that the role of MFG may have been underestimated based on research with alphabetical languages.

A third finding of our study is the strong involvement of the right hemisphere in Chinese character recognition. The fact that Chinese word recognition involves more bilateral processing than word recognition in alphabetical languages has been reported before (Bolger et al., 2005). Hsiao and Lam (2013) hypothesized that this could be because Chinese characters require less high spatial frequency processing than alphabetical words. Another explanation may be that the left and the right character halves are processed largely independently up to a rather late stage of word recognition. Such a theory was presented by Shillcock et al. (2000) to explain how the brain could deal optimally with visually presented words that are split in the middle because of the foveal split. Although the theory did not receive much support in alphabetical languages (McCormick et al., 2010), it may offer a good explanation for Chinese character recognition, where there is a cleaner division of semantic and phonological information. The former is predominantly presented in the left stimulus half (sent to the right hemisphere), whereas the latter is most often presented in the right stimulus half (transmitted to the left hemisphere). It may be that the division of labor is maintained in initial stages of word processing, also because the same radicals can be used as semantic and phonetic radicals at the same time.

Tan et al. (2005) further reported that Chinese word recognition includes a parietal region on the border of SPL/IPL, whereas alphabetical languages induce more activation in the angular gyrus. They attributed this difference to the fact that logographic scripts involve less assembled phonology (in the angular gyrus) and more stored phonological representations (in SPL/IPL). The involvement of the SPL/IPL region was confirmed in our study. This region coincides with the intraparietal sulcus, which is also relevant for ordinal information (Fias et al., 2007), in line with the finding that the contribution of radical combinability is position dependent. On the other hand, Hagoort (2014) pointed to the existence of strong connections between this brain region and the pars opercularis of IFG and also in speakers of alphabetic languages. A careful comparison of these connections in Chinese speakers and English speakers may further clarify the various contributions of SPL/IPL to visual word processing in different scripts.

SPL and precuneus also seem to be more involved in Chinese character recognition than in alphabetical words. The most likely reason for this is the stronger visuospatial component in Chinese characters. The finding that activity in these areas correlates with logographeme information is in line with this hypothesis. The logographeme level refers to basic stroke combinations that form radicals and characters. Our findings suggest that logographemes and their position to each other may be a more important aspect in Chinese character recognition than GRC or the number of strokes (Han et al., 2007).

Regarding to the importance of visual input information at early processing stages in posterior regions, the only variable correlating with neural activity in FG (vOT) was the number of strokes in the whole character (NSC), in line with previous literature (Chen et al., 2016). There was some evidence for a correlation with SRC, but this seems weak and needs to be replicated before we can think of its contribution. The absence of strong SRC and logographeme correlations in FG suggests that this...
region is mainly engaged in whole-word representations rather than in the fine sublexical level, which is consistent with our findings of the multivariable analysis. There was more involvement of the left hemisphere FG, which is somewhat surprising, given the large right hemisphere contribution in higher language areas. The brain asymmetry is in line with Strother et al.’s (2016) observation that there is more transfer of verbal information from right hemisphere to left hemisphere in visual cortex than the other way around. This would be in line with the overall larger contribution of the left hemisphere to visual word recognition.

There were also correlations between sublexical characteristics and cerebellum activity, in line with the finding that the cerebellum is heavily involved in word reading (Alvarez and Fiez, 2018), also in Chinese (Chen et al., 2016). An ROI analysis taking into account all possible confounds, showed evidence for correlations with the SRC in left hemisphere and logographeme in right hemisphere. We wait for more evidence before interpreting this finding.

The paradigm we used allowed us to conclude that SRC is a better measure of radical combinability than GRC, at least when SRC was defined in terms of the left or right half of two-radical characters. This opens the way for future, more detailed experiments. In Chinese characters the radical position is confounded with radical information. Most radicals in the left half convey semantic information, whereas most in the right half contain phonological information. This raises the question of whether the effects we observed are primarily because of position-dependent combinability (left vs right) or to function-dependent combinability (semantic vs phonological). This can be investigated with a design similar to the one we used, with SRC (and GRC) controlled and the function of the radical manipulated.

In summary, our data provide novel evidence that Chinese word recognition involves decoding and combining sublexical units. Two functional units seem to be important, radicals combined with their position (SRC) and logographemes. When these two variables are taking into account, not much information seems to be left in GRC. Bilateral IFG and MFG are strongly involved in the processing of SRC information, whereas logographeme information is processed predominantly in parietal cortex (SPL/IPL). Because a semantic task was used, we feel certain that the findings generalize to Chinese reading for meaning and are not confined to the form-focused lexical decision task.

References


