Neural correlates of foveal splitting in reading: Evidence from an ERP study of Chinese character recognition

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Abstract

Recent research on foveal structure and reading suggests that the two halves of a centrally fixated word seem to be initially projected to, and processed in, different hemispheres. In the current study, we utilize two contrasting structures in Chinese orthography, "SP" (the semantic radical on the left and the phonetic radical on the right) and "PS" characters (the opposite structure), to examine foveal splitting effects in event-related potential (ERP) recordings. We showed that when participants silently named centrally presented characters, there was a significant interaction between character type and hemisphere in N1 amplitude: SP characters elicited larger N1 compared with PS characters in the left hemisphere, whereas the right hemisphere had the opposite pattern. This effect is consistent with the split fovea claim, suggesting that the two halves of a character may be initially projected to and processed in different hemispheres. There was no such interaction observed in an earlier component P1. Also, there was an interaction between character type and sex of the reader in N350 amplitude. This result is consistent with Hsiao and Shillcock's [Hsiao, J. H., & Shillcock, R. (2005b). Foveal splitting causes differential processing of Chinese orthography in the male and female brain. *Cognitive Brain Research*, *25*, 531–536] behavioural study, which showed a similar interaction in naming response time. They argued that this effect was due to a more left-lateralized network for phonological processing in the male brain compared with the female brain. The results hence showed that foveal splitting effects in visual word recognition were observed in N1 the earliest, and could extend far enough to interact with the sex of the reader as revealed in N350.
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Keywords: Foveal splitting; Event-related potential; Chinese character recognition

1. Introduction

In Chinese orthography, a dominant type of character, the phonetic compound, comprises about 81% of the 7000 frequent characters (Li & Kang, 1993). A Chinese phonetic compound character consists of a semantic radical, which usually reflects the meaning of the character; and a phonetic radical, which typically supplies partial information about the pronunciation of the character. In Chinese orthography, the phonetic radical types outnumber the semantic radical types by about 10–1. Hence,

within a phonetic compound, there is more variation in the phonetic radical than the semantic radical; in other words, in a phonetic compound the side on which the phonetic radical appears is more informative.

A majority of these Chinese phonetic compounds have a left–right structure, with the two radicals standing side by side; about 90% of them have the semantic radical on the left and the phonetic radical on the right (SP characters), and the other 10% have the semantic radical on the right and the phonetic radical on the left (PS characters; Fig. 1). In other words, the ratio of SP to PS character types is about nine to one. In the use of Chinese characters, as reflected in the token frequency of the characters, the ratio between SP and PS characters is about 5.5 and 1. Given the dominant distribution of SP characters compared with PS characters, together with the internal information structure of the characters which is skewed to where the phonetic radical typically appears, the overall information distribution among all

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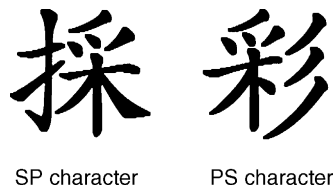
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SP character   PS character

Fig. 1. Examples of SP and PS characters. The SP and PS characters, meaning "to pluck" and "to color", respectively, share the same phonetic radical and have the same pronunciation as 'cai3' in Pinyin, a spelling system based on the Latin alphabet.

left-right structured phonetic compounds is skewed to the right (Hsiao & Shillcock, 2006).

In recent years, there has been converging evidence showing that human foveal representation is functionally split about a vertical meridian, with each hemifield initially projected contralaterally to the relevant hemisphere. The evidence has come in part from visual hemifield studies of commissurotomy and callosal agenesis patients (e.g., Fendrich & Gazzaniga, 1989; Harvey, 1978; Lines, 1984) and from neuroimaging studies (e.g., Gray, Galetta, Siegal, & Schatz, 1997; Portin & Hari, 1999). This foveal splitting phenomenon has also been reported to have important implications in visual word recognition (e.g., Brysbaert, 2004; Shillcock, Ellison, & Monaghan, 2000). A number of studies of lexical processing have examined previously reported hemispheric differences in visual hemifield studies (i.e., presenting target words in different visual hemifields) with foveally presented lexical stimuli and found that different processing styles of the left hemisphere (LH) and right hemisphere (RH) have affected the parts of the word to the right and left of fixation, respectively. A number of psycholinguistic experiments have supported predictions of the split fovea claim, involving phenomena such as the optimal viewing position effect (Brysbaert, 1994), the word length effect (Lavidor, Ellis, Shillcock, & Bland, 2001), the orthographic neighbourhood effect (e.g., Lavidor, Hayes, Shillcock, & Ellis, 2004; Lavidor & Walsh, 2003), and case alternation effects (Ellis, Brooks, & Lavidor, 2005).

According to the split fovea claim, in Chinese character recognition, when a Chinese SP or PS character is fixated between the phonetic and semantic radicals, the two radicals are initially projected to different hemispheres. The difference between the semantic and phonetic radicals and the overall information skew within SP and PS characters tends to present the two hemispheres with different processing problems and hence provides an important opportunity for examination of hemispheric processing in reading (Hsiao & Shillcock, 2004, 2005a,b).

Despite the converging evidence in support of a functional split in human foveal processing, it is still a controversial claim with respect to the precision of foveal splitting and how far the effects of foveal splitting extend from the retina into the higher processing associated with visual word recognition. In a Chinese SP character recognition task, Hsiao, Shillcock, and Lavidor (2006) showed that when characters were centrally presented with the fixation point between the two radicals, applying repetitive transcranial magnetic stimulation (rTMS) over left occipital cortex, but not right occipital cortex, impaired the facilitation

of semantic radicals with large combinability (i.e., semantic radicals that could combine with a large number of different phonetic radicals); their results hence suggested that foveal splitting may be precise enough to project the two radicals of a centrally presented character to different hemispheres. In a Chinese character naming experiment, they further demonstrated that the effects of foveal splitting in reading reach far enough into word recognition to interact with the sex of the reader (Hsiao & Shillcock, 2005b). In their experiment, they presented the participants with isolated Chinese SP and PS characters with the fixation point between the phonetic and semantic radicals such that the two radicals may be initially projected to different hemispheres. They measured the participants' response times in naming the characters; the results exhibited a significant interaction between sex and position of the phonetic radical (i.e., SP versus PS characters): males responded to SP characters significantly faster than to PS characters; in contrast, females had a non-significant tendency in the opposite direction. They interpreted the results in terms of the more left-lateralized network for phonological processing in the male brain tending to be superior in the processing of the majority SP characters, in which the phonetic radical is initially projected directly to the LH, at the expense of the minority PS characters; in contrast, the typically less lateralized network for phonological processing in the female brain (e.g., Shaywitz et al., 1995; Voyer, 1996) tended to have more equivalent processing of PS and SP characters. This phenomenon was also predicted by an implemented connectionist model of Chinese character pronunciation in which the hidden layer of the architecture could be composed of two partially encapsulated sets of hidden units (the split model) or a single, monolithic set of hidden units (the non-split model) (Hsiao & Shillcock, 2004, 2005a). The model was trained to map Chinese orthography onto Chinese phonology. In terms of sex differences, the non-split model was seen as simulating the male brain, in which phonological processing happens predominantly in just one hemisphere (the LH), and the split model was seen as simulating the female brain, in which phonological processing is more distributed between the two hemispheres. The modelling data showed a similar interaction (in output error) between model architecture (non-split versus split) and position of the phonetic radical; the results hence matched well with the behavioural data.

The results obtained in Hsiao and Shillcock' (2005b) study have confirmed that foveal splitting is precise enough to project the two radicals of a Chinese phonetic compound to different hemispheres, and its effects can extend far enough in visual word recognition to interact with the sex of the reader in a relatively naturalistic reading experiment. In the current study, we conduct a corresponding electroencephalogram (EEG)/event-related potential (ERP) examination to explore the electrophysiological reflection of the observed foveal splitting phenomena, so as to utilize the distinct contrasting structures of Chinese SP and PS characters to understand better the temporal profile of foveal splitting processing in reading. With this technique, we can compare the recorded ERP patterns when participants attempt to name a PS or an SP character, and examine whether there is differential processing of the two types of characters that

demonstrates the effect of foveal splitting in reading and its time course.

According to an MEG study conducted by Pammer et al. (2004), early visual information for word reading is initially processed in occipito-temporal areas contralateral to the stimulated hemifield, also predominantly in the LH posterior fusiform gyrus, in the time window between 0 and 200 ms, and subsequently transferred to the visual word form area (VWFA) within the time window 100–300 ms after stimulus presentation. Consistent with the MEG data, early ERP components are usually identified within 200 ms post-stimulus. For example, Cohen et al. (2000) reported a negative potential occurring 150–160 ms post-stimulus strictly contralateral to stimulation recorded from posterior electrodes. In a visual rhyming task with English stimuli, Grossi, Coch, Coffey-Corina, Holcomb, and Neville (2001) reported P120 (P1) and N180 (N1) over occipital sites, and N120 and P200 over anterior temporal sites. Liu and Perfetti (2003) reported that in a Chinese character delayed naming task, the posterior regions, which support visual analysis or word form identification, activated early within 200 ms, whereas the anterior regions generally activated later. Bentin, Mouchetant-Rostaing, Giard, Echallier, and Pernier (1999) reported a negative potential N170 (N1) in a visual oddball task, elicited in the occipito-temporal sites, which was larger for alphabetic orthographic than for non-orthographic stimuli in the LH and vice versa in the RH. Rossion, Joyce, Cottrell, and Tarr (2003) also reported a left-lateralized N170 (N1) for word stimuli during 130–170 ms post-stimulus in a word orientation judgement task.

According to the split fovea claim, two halves of a centrally presented character are initially projected to and processed in different hemispheres. In other words, in the current study, the centrally presented SP and PS characters may present the brain with different processing problems because of their different information structures. If it is true that human fovea is precisely split, we expect that differences between the visual analyses and the orthographic processing of the two types of character and their interaction with the two hemispheres may be reflected in early components before 200 ms.

As for late components after 200 ms post-stimulus, the activation in VWFA, which has been argued to be in the middle portion of the LH fusiform gyrus, was reported to appear around the time window 100–300 ms post-stimulus (Pammer et al., 2004). This area was reported to respond with increased activation to words compared with consonant strings and demonstrate retinal position invariance (Cohen et al., 2000, 2002). Bentin et al. (1999) reported a negative potential N320 in a phonological/phonetic decision task, which was only elicited by pronounceable stimuli, and a more broadly distributed negative potential N350 in a phonological/lexical decision task, which was only elicited by phonologically legal stimuli. Grossi et al. (2001) reported an N350 component in a visual rhyming task which had a left anterior temporal distribution, larger over the LH from frontal to parietal sites, but not at occipital sites. This component may be an index of LH specialization during reading (Neville, Kutas, & Schmidt, 1982). Hence, Grossi et al. (2001) argued that the decreasing amplitude with age suggests that such LH reading processes become more efficient with age. Pammer et al.

(2004) also reported activation in the posterior superior inferior frontal gyrus (IFG) temporally preceding the activation in the VWFA region. This area has been found to be associated with fine-grained phonological processing and activated during silent reading and naming (see Fiez & Petersen, 1998). Thus, if the effect of foveal splitting extends far enough to interact with the sex of the reader in character pronunciation tasks, as observed in the behavioural data reported by Hsiao and Shillcock (2005b), we expect to see this effect being reflected in a late component elicited between 250 and 400 ms post-stimulus, possibly an N350 component as identified in Grossi et al.'s study (2001).

2. Methods

2.1. Stimuli

The materials consisted of the same 75 pairs of Chinese phonetic compound characters as those in Hsiao and Shillcock's (2005b) behavioural study. Hence, each pair of characters shared the same phonetic radical (Fig. 1); the two characters in each pair were matched in terms of their pronunciation and token frequency; the two groups of characters were matched as closely as possible for semantic concreteness, syntactic class, and semantic radical visual complexity as defined by number of strokes. The mean number of strokes of the semantic radical of the SP characters was 4.45, and that of the PS characters was 4.76. The phonetic radicals typically have more strokes than semantic radicals on average in Chinese orthography. Character frequencies were within a mid to high range (Huang, 1995); very low frequency characters were avoided. According to Huang (1995), the average frequency count of the SP characters was 9971; that of the PS characters was 15,256; there was no significant difference between the two lists in frequency count (paired t-test, $n.s.$). In a further test of the materials, eight male and eight female native Chinese speakers judged whether the characters had a male- or female-oriented meaning, and there was no significant gender bias between the meanings of the SP and PS character pairs ($F(1, 24) < 1$). The same fillers as in the above study, consisting of 40 SP and 20 PS characters, were used in the current study. These filler characters were included to prevent participants from being aware of the design of the materials during the experiment; that is, they were pairs of characters with the same phonetic radical.

2.2. Participants

We recruited 18 female and 17 male native Chinese speakers in Taiwan; they were all university students, had normal or corrected vision. After performing artefact rejection, we removed two females and one male from the analyses, due to the extremely small number of valid trials in their data (less than 20). The 16 males and 16 females whose data were analyzed were all right-handed according to the Edinburgh handedness inventory (Oldfield, 1971); the mean laterality quotient for the male group was 95.69%, and the mean laterality quotient for the female group was 98.81%. They were between 20 and 32 years old, with ages closely matched between the male and female groups. The average age of the males was 23 years and 10 months, and the average age of females was 24 years 6 months.

2.3. Design

The design of this study had a between-subject variable: sex (male versus female), and three within-subject variables: character type (PS versus SP characters), hemisphere (left versus right), and electrode site (which level depends on the number of electrodes selected for each component). The ERP recordings for the two types of character were averaged separately at each electrode site for each participant. ERP components were identified on the time dimension, and electrodes that had prominent peaks were selected for analyses. Electrodes were selected in pairs, that is, corresponding electrodes in the two hemispheres. The dependent variables were amplitude of each ERP component identified.

500 ms	150 ms	1300 ms	700ms	1200 ms	800ms

Prompting lines · Target character or number · Mask · Critical trials: Blank. · Blink signal · Blank
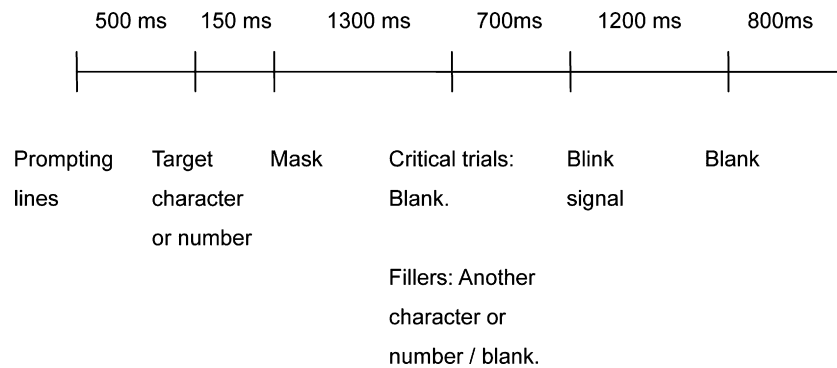
Fillers: Another character or number / blank.

Fig. 2. Timeline of the experiment.

During the experiment, binocular vision was used. Characters were presented in a standard calligraphic font and in the same size. The size of the characters was approximately $1\,cm \times 1\,cm$. Participants were sitting in front of a screen with a 92 cm distance from their nasion to the screen. Hence, the character spanned less than one degree of visual angle. This limit was applied to ensure that the stimulus presented fell within foveal vision, and approximated the size of normal, screen-presented Chinese text. Every subject was presented with all characters in the materials. These stimulus parameters were the same as those in the associated naming study. The design and control of this experiment was through the psychology software E-Prime v1.1.

2.4. Procedure

The task in the current study was a delayed homophone judgement task, in order to record EEG patterns corresponding to the silent pronunciation of the character. The homophone judgement ensured that the phonology of the character was being activated in the brain, without motor preparation and activation resulting from reading out the character. Each trial began with two vertical short lines presented on the screen for 500 ms. Participants were required to look at the middle point between the two short lines, which was approximately the boundary between the phonetic and semantic radicals when a character was presented. They were asked not to move their eyes or blink once a trial began. The two short lines were followed by a brief, 150 ms presentation of the target character; this presentation time was intended to be too short for a refixation to occur. As in Hsiao and Shillock's (2005b) study (cf. Brysbaert, 1994), occasionally a 9 pt. digit was presented, instead of a character, between the two lines where participants should have been fixating, and they were required to make a delayed same–different judgment of two consecutively presented digits. Data from any participant who did not respond to the digits with an acceptable accuracy were excluded. This design was to ensure that participants were fixating the designated fixation point.[1] Before the experiment, we also explicitly explained to each participant the importance of fixating the designated fixation point at all times when they see the prompt. Thus, according to the split fovea claim, the two radicals of a presented character would be initially contralaterally projected to different hemispheres.

After each presentation of a target character/digit, participants were asked to mentally name the target character or digit and keep the pronunciation in mind. We made sure that participants understood the requirement to silently name the target character for recording purpose. The stimulus was replaced by a mask which stayed on the screen for 1300 ms. In the trials where a filler character or a digit was presented, another character or digit would appear after the mask. This character was not a phonetic compound character, and hence does not have a phonetic radical; it also did not share any radical with the target character. Participants were asked to judge whether the two characters were homophones

or whether the two digits were the same by pressing the relevant buttons on a response box with four buttons. They were asked to press the inner buttons with their left and right index fingers simultaneously for a positive response and to press the outer buttons with their left and right middle fingers simultaneously for a negative response. This design was to avoid any hemispheric bias that may be caused by responding with one hand (cf. Mohr, Pulvermuller, & Zaidel, 1994). In the rest of the trials, no further character or digit was provided. The second character or digit stayed on the screen for 700 ms, followed by a "B" (for "blink") presented for another 1200 ms. Participants were asked to blink at least once when they saw this signal, and not to blink otherwise. This design was to reduce the number of trials contaminated by blinks due to eye tiredness. The screen then turned blank for 800 ms before the start of the next trial. Participants had no opportunity to correct responses; and no feedback was given during the experiment. The timeline of this task is shown in Fig. 2.

The characters in the materials were divided into four blocks evenly, with each block containing 10 numbers, 15 fillers, 18 or 19 SP characters, and 18 or 19 PS characters from the 75 SP–PS pairs. In total, there were 62 or 63 trials in each block. The SP and PS characters in the same pair were prevented from appearing in the same block. Participants were put into two groups, with males and females evenly distributed. The presentation order of each pair of PS and SP characters was counterbalanced across the two groups. Characters in each block were presented in a random order. Other procedural details were the same as those in Hsiao and Shillock's study (2005b).

2.5. ERP recording and analysis

The EEG was recorded from a 64-channel Neuroscan version 4.3 system with a common vertex reference, and transformed into a computer-averaged ears reference (M1 + M2) before analyses. This reference procedure has been used in several asymmetry studies and may be considered as a current standard method for EEG asymmetry research (Hagemann, Naumann, & Thayer, 2001). Electrodes were also placed above and beneath the left eye to monitor vertical eye movements, and at the outer canthus of the left and right eyes to monitor horizontal eye movements. The recording from these electrodes were used to reject trials contaminated by eye artefacts. Trials contaminated by muscular activities, electrical noise, or other unknown noise were also excluded from the analyses by rejecting data with extreme values, abnormal trends, and abnormal distribution. We used functions provided in EEGLAB (Delorme & Makeig, 2004) to perform artefact rejection. The rejection process consisted of four steps: first, we rejected epochs with extreme values larger than $25\,\mu V$ or smaller than $-25\,\mu V$ for all channels. Second, we rejected epochs that had abnormal trends by rejecting epochs with a slope larger than $50\,\mu V$/epoch or had a regression R-square larger than 0.3. Third, we rejected epochs with improbable data, that is, the epochs with values larger or smaller than six standard deviations from the mean of the probability distribution for each single electrode, or five standard deviations from the mean of the probability distribution for all electrodes. Finally, we rejected epochs with abnormally distributed data by rejecting epochs with kurtosis outside of five standard deviations of the mean kurtosis value, for each single electrode and across all electrodes. We also applied independent component analysis to the data of each participant and performed rejection on the derived components that were characterized by typical muscle artefacts or line

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[1] Note that despite these stringent measures, it may be that the method we used introduces a degree of noise into the exact positioning of the fixation point. A better way to ensure participants' fixation may be to use techniques such as gaze contingent display to more effectively monitor participants' eye fixation behaviour.

noise artefacts; examples of these artefact components are given in the EEGLAB tutorial (Delorme, Serby, & Makeig, 2004). These data rejection methods were suggested and provided by the EEGLAB toolbox (Delorme & Makeig, 2004). After removing artefacts, ERPs from the SP and PS characters were averaged separately over an epoch of 1022 ms, including a 100 ms prestimulus baseline. This length of epoch corresponded to 512 data points with a sampling rate of 500 Hz.

Based on results from previous ERP studies regarding phonological processing in visual word recognition (e.g., Bentin et al., 1999; Grossi et al., 2001; Liu & Perfetti, 2003), the components of interest in this study were early components around 150 ms post-stimulus over posterior electrodes in the occipitotemporal areas, and late components around 350 ms post-stimulus over anterior electrodes; these components may be related to visual word form representation and phonological processing, respectively. Each ERP component was labelled according to its polarity and its mean peak latency. For early components, amplitude was measured as peak amplitude over a time window; for broader late components, amplitude was measured as mean amplitude over a time window (cf. Grossi et al., 2001).

For each component, we also performed source localization with the Laplacian weighted minimum norm (LORETA) algorithm (Pascual-Marqui, 1999; Pascual-Marqui, Michel, & Lehmann, 1994). The algorithm calculates neuronal generator distribution according to an underdetermined (distributed) source model, in which each point of a 3D grid of solution points is considered a possible current source location, and the task is to find a configuration of the current source activity that explains the surface potentials. The LORETA algorithm selects the solution with a smooth spatial distribution that minimizes the Laplacian of the weighted sources, that is, the smoothest solution. The source localization procedure was performed on the grand average ERPs. We used LORETA-KEY software package to conduct the source localization (Pascual-Marqui et al., 1994). The software uses a three-shell spherical head model registered to a standardized stereotactic space (Talairach & Tournoux, 1988). The solution space of the model is confined to cortical grey matter. A spatial resolution of 7 mm is used, and in total there are 2394 voxels.

3. Results

After artifact rejection, we removed one male and two female participants from the analyses due to extremely low numbers of valid trials in each condition (fewer than 20). After removing these participants, there were 16 males and 16 females in the final analyses; the average number of valid trials in the male-PS condition was 60; that in the male-SP condition was 59; the female-PS condition had 62 valid trials on average, and the female-SP had 61. All of the 16 male and 16 female participants achieved above 95% accuracy in the digit judgement task, and the average was 99.6%; hence, none of them was further removed from analyses. They also performed very well in the homophone judgement task: all of them had accuracies above 96%, and the average was 99.5%.
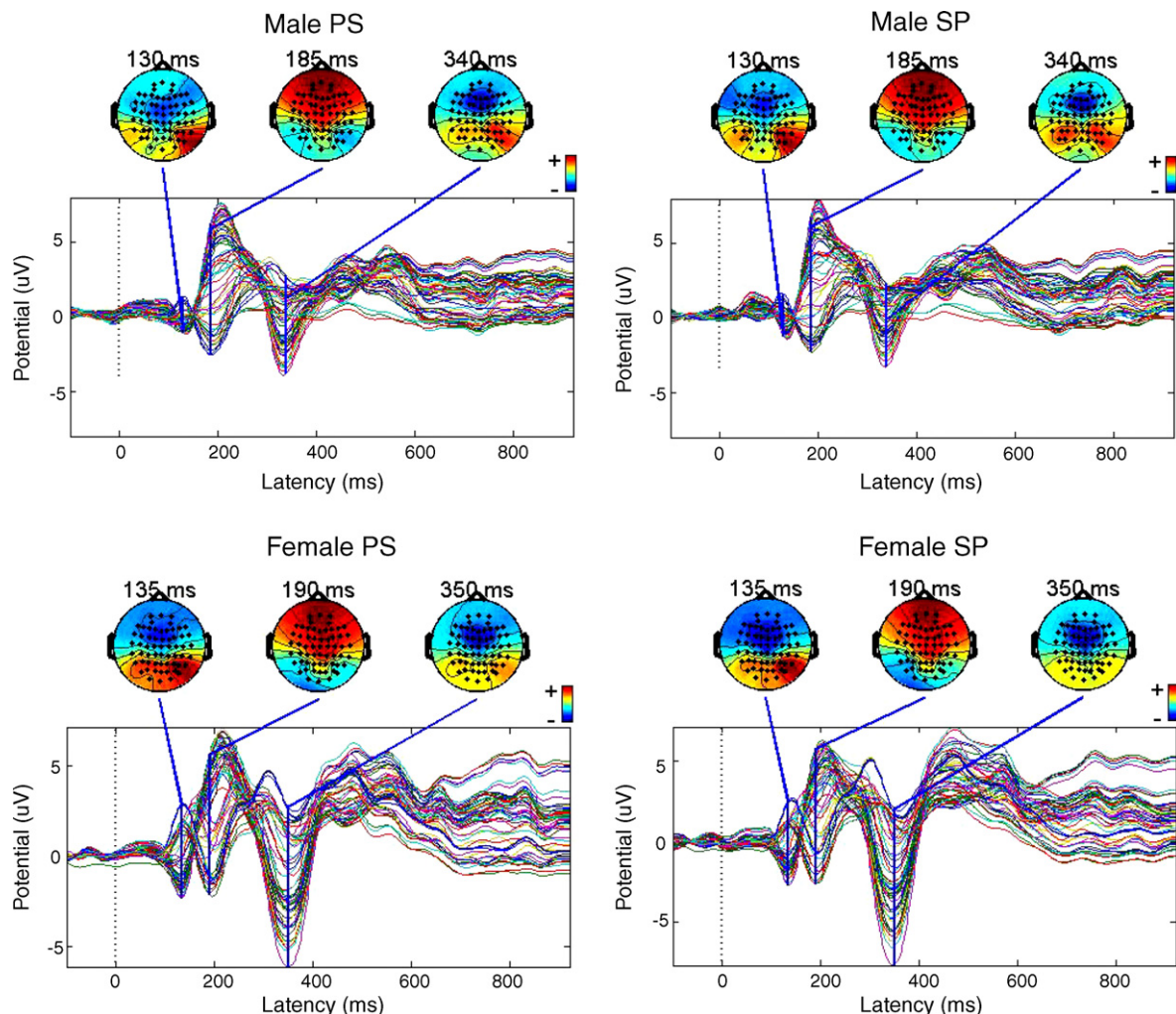

Fig. 3. Grand average topographies in all condition with components of interest marked. Top left: male-PS; top right: male-SP; bottom left: female-PS; bottom right: female-SP.
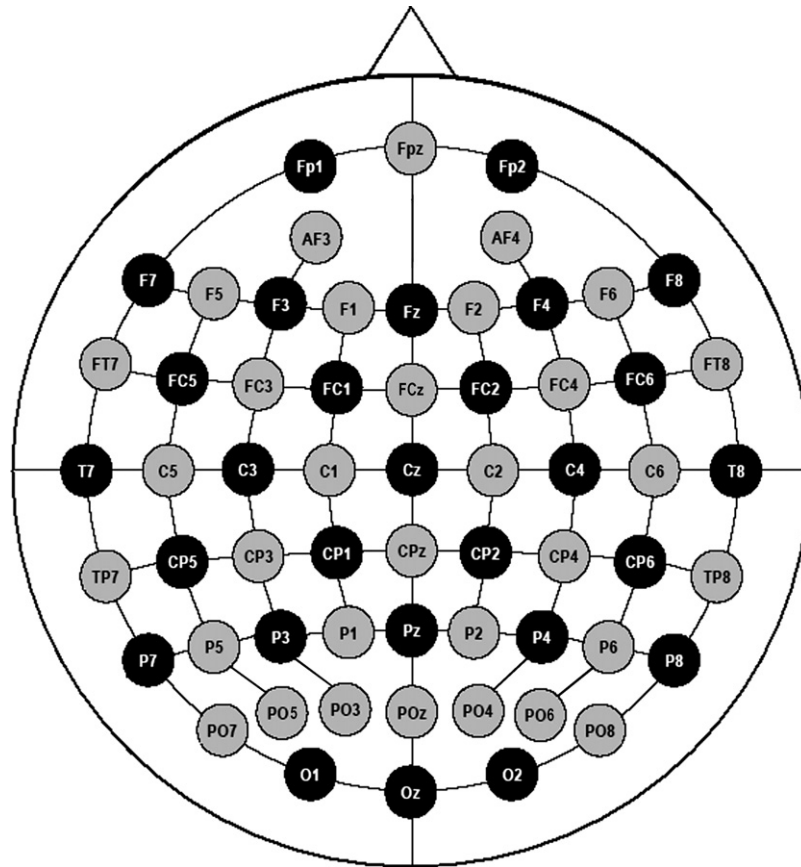
Fig. 4. Electrode distribution.

Fig. 3 shows the grand average topographies in all conditions. As shown in the figure, three major components were identified on the time dimension: one at around 120–140 ms, the other at around 180–200 ms, and another at around 330–360 ms post-stimulus. For each observed component, we selected the electrodes that had prominent peaks in the two hemispheres for statistical analyses. For current purposes, we examined the electrodes that had prominent positive peaks for the first component, and termed it P1, referred to as the first positive component observed after the stimulus onset. The electrodes in the LH were: PO7, PO5, P7, and P5; those in the RH were: PO8, PO6, P8, and P6 (see Fig. 4 for the electrode distribution). For the second component, we examined the electrodes that had prominent negative peaks and termed this component N1, to match the N1 component observed in previous ERP studies of visual word naming (e.g., Cohen et al., 2000; Grossi et al., 2001). The first two components had very similar distributions (except that the polarity was opposite to each other), and hence the same set of electrodes was selected for analyses. For the third component, we examined the electrodes that had prominent negative peaks and termed it N350; the electrodes selected were F1, F3, FC1, and FC3 in the LH, and F2, F4, FC2, and FC4 in the RH. The components and their latencies observed hence were consistent with previous ERP studies concerning phonological processing in visual word recognition (e.g., Bentin et al., 1999; Grossi et al., 2001; Liu & Perfetti, 2003).

For each component, the amplitude was measured over a 50 ms window centred around the peak latency of the maximum amplitude on the grand-averaged data, separately for each hemisphere and condition. In order to examine possible electrode site effects regardless of differences in mean amplitude between subjects, the amplitude measured from different sites was normalized for each subject according to the following formula: (ERP amplitude − mean ERP amplitude across all sites)/standard deviation (Grossi et al., 2001; McCarthy & Wood, 1985). This normalization eliminated possible main effects in mean amplitude difference between subjects, but was necessary to discover genuine interactions between amplitude and other variables, such as electrode site, which were of interest in this study. The statistical analysis method used was repeated-measures ANOVA; Greenhouse–Geisser correction was applied to variables that had more than two degrees of freedom (i.e., electrode site).

3.1. Early components in the posterior regions: P1 and N1

3.1.1. P1

The first component on the time dimension was observed at around 120–140 ms (Fig. 3), and we analyzed the positive inflection, P1, over the posterior ventral sites. P1 peaked at 130 ms post-stimulus in the male group and at 135 ms in the female group. Its peak amplitude was found to be larger in the RH than in the LH ($F(1, 12) = 8.221$, $p < 0.05$ with normalization;
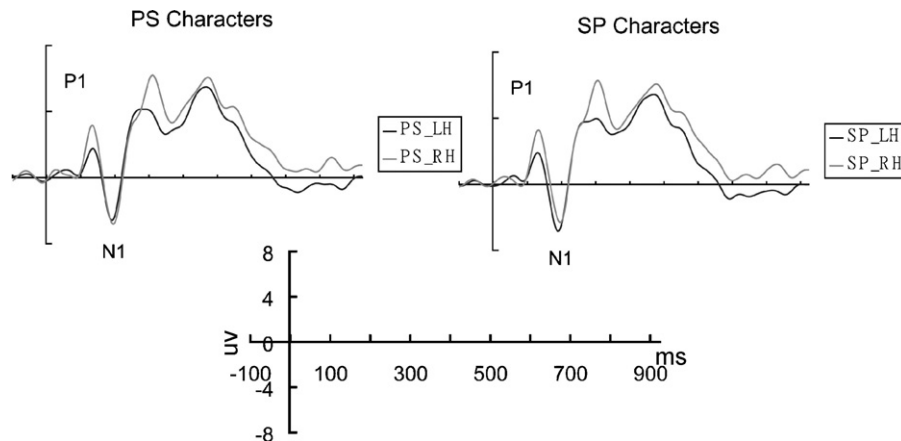
Fig. 5. P1 and N1 elicited by SP and PS characters over the left and right posterior regions. The amplitude was averaged across the four selected electrode in the LH (P5, P7, PO5, PO7) and the RH (P6, P8, PO6, PO8).
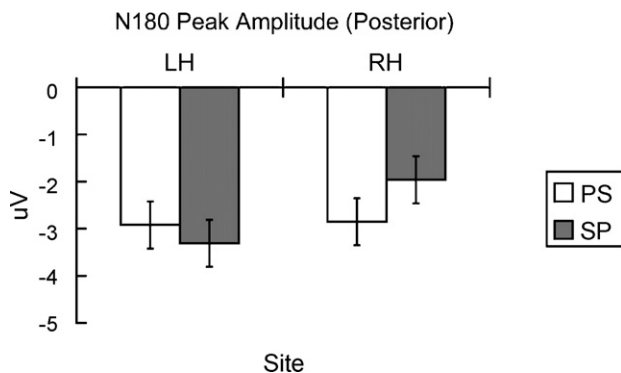

Fig. 6. Interaction between character type and hemisphere in N1 peak amplitude. The error bars show standard errors. The amplitude values were not normalized.

$F(1, 12) = 7.735$, $p < 0.05$ without normalization; Fig. 5[2]; this effect did not interact with the electrode sites we selected ($F(3, 36) = 1.103$, n.s. with normalization, $e = 0.609$; $F(3, 36) = 1.614$, n.s. without normalization, $e = 0.571$; Greenhouse–Geisser correction was applied). No other effect was observed for this component; the interaction between character type and hemisphere was not significant ($F(1, 12) = 1.138$, n.s. with normalization; $F(1, 12) = 0.560$, n.s. without normalization), suggesting that there was no effect of foveal splitting observed at this stage.

3.1.2. N1

The other component was observed at around 180–200 ms post-stimulus, and we analyzed the negative inflection, N1, over the posterior ventral sites. N1 peaked at around 185 ms in the male group and at 190 ms in the female group. There was no main effect in N1 peak amplitude. However, as shown in Figs. 5 and 6, N1 peak amplitude exhibited a significant interac-

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[2] Note that the source localization was performed on a population average. Brain anatomy and cap displacement usually differ from participant to participant. Hence, the generator distribution data presented here may be just a rough estimate. Brain imaging techniques that have higher spatial resolution, such as fMRI and MEG, are required for identifying the exact locations of the neuronal generators.

tion between character type and hemisphere ($F(1, 18) = 18.561$, $p < 0.001$ with normalization; $F(1, 18) = 10.238$, $p < 0.01$ without normalization), with a larger amplitude for SP characters than PS characters in the LH, and a larger amplitude for PS characters than SP characters in the RH. This effect did not interact with the electrode sites we selected ($F(3, 54) = 0.254$, n.s. with normalization, $e = 0.519$; $F(3, 54) = 0.365$, n.s. without normalization, $e = 0.655$; Greenhouse–Geisser correction was applied). Hence, a hemispheric difference between the processing of SP and PS characters was observed in N1 peak amplitude.

In a separate analysis, we analyzed the positive inflection over the anterior regions at about the same time window as N1, and termed it P200. P200 peaked at about 205 ms post-stimulus (Fig. 3), and we picked the electrodes that had prominent positive peaks in the two hemispheres for analyses, including FP1, AF3, F1, F3, FC1, and F3 in the LH, and FP2, AF4, F2, F4, FC2, and FC4 in the RH. The same as N1, the peak amplitude of P200 also exhibited a significant interaction between character type and hemisphere ($F(1, 25) = 4.769$, $p < 0.05$ with normalization; although it was not significant in the data without normalization: $F(1, 25) = 2.287$, n.s.); this effect did not interact with the electrode sites we selected ($F(5, 125) = 1.654$, n.s. with normalization, $e = 0.491$; Greenhouse–Geisser correction was applied). Hence, it is possible that N1 and P200 were two directions of the same dipole activity, and P200 activity over the anterior regions reflected volume-conducted activity originally generated in the posterior regions (i.e., N1; cf. Rossion et al., 2003; Schweinberger, Pickering, Jentzsch, Burton, & Kaufmann, 2002).

3.2. Late component: N350

The component observed after 250 ms was a negative deflection peaking at around 350 ms (N350). N350 peaked at around 340 ms in the male group and at 350 ms in the female group. There was a significant interaction between character type and sex ($F(1, 23) = 4.973$, $p < 0.05$ with normalization; $F(1, 23) = 5.949$, $p < 0.05$ without normalization; Figs. 7 and 8): PS characters had larger N350 amplitude (i.e., more negative) than
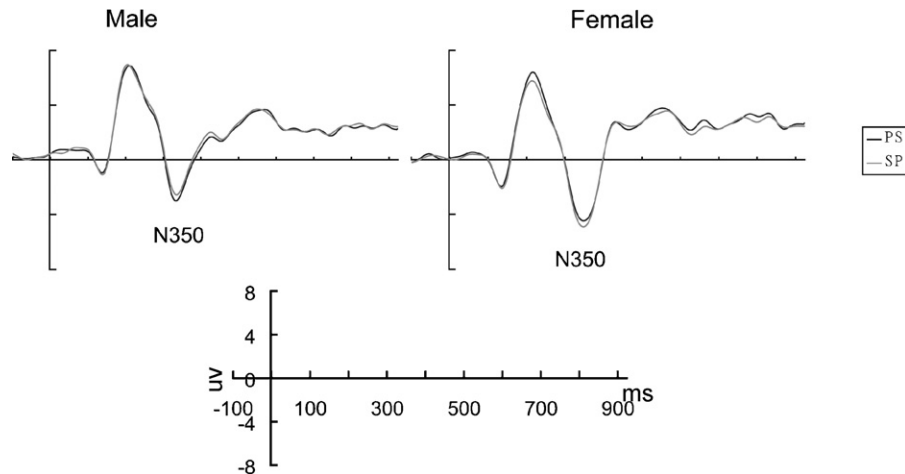
Fig. 7. N350 elicited by SP and PS characters over the left and right anterior dorsal regions. The amplitude was averaged across the four selected electrode in the LH (F1, F3, FC1, FC3) and the RH (F2, F4, FC2, FC4).
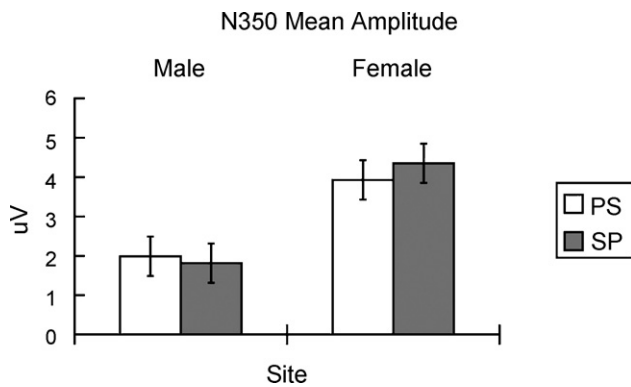

Fig. 8. Interaction between character type and sex in N350. Error bars show standard errors. The amplitude values were not normalized.

SP characters in the male group, whereas an opposite pattern was observed in the female group; this effect did not interact with the electrode sites we selected ($F(3, 69) = 1.071$, *n.s.* with normalization, $e = 0.611$; $F(3, 69) = 0.990$, *n.s.* without normalization, $e = 0.483$; Greenhouse–Geisser correction was applied). This interaction was consistent with the sex by character type interaction observed in the corresponding behavioural character naming study (Hsiao & Shillcock, 2005a,b).

We also performed source localization with LORETA on the grand average data. Fig. 9 shows the estimated neuronal generator distribution of the three components identified at their peak latency based on the global field power data (see also Table 1). As shown in the figure, the source distribution for P1 was primarily in bilateral medial occipital lobe (BA 18 and 19) and had larger density in the RH. For N1, the source distribution was centred on BA 37 in the RH, that is, the fusiform gyrus and inferior temporal gyrus. For N350, the generator distribution had the strongest density at BA 7 in the parietal lobe of the LH[3]; another weaker local maximum of the estimated density was observed in BA37, which coincided with the centre of the N1 source distribution.

4. Discussion

The components observed in the current study on the time dimension were consistent with previous studies of visual word recognition (e.g., Grossi et al., 2001). We analyzed early components of interest, P1 and N1, over the posterior ventral electrodes and the late component of interest, N350, over the anterior electrodes.

4.1. Early components of interest: P1 and N1

Traditionally in the ERP literature, early components identified during 50–150 ms post-stimulus onset have been considered indices of the information flow going through a hierarchical visual system (Sereno & Rayner, 2003) and also early auditory processing (Eggermont & Ponton, 2002). Foxe and Simpson (2002) have shown that the initial trajectory of visual activation flow is a fast and widespread sweep which activates sensory, parietal, and frontal areas in less than 30 ms, and continues through iterations of feedback loops for further processing in the sensory area (see also Buchner et al., 1997). Given the timing of the early ERP components observed, they might result from the recurrent feedback loops in visual information processing, rather than the first direct sweep through the system (Sereno & Rayner, 2003).

4.1.1. P1

In the current study, the peak amplitude of the earliest component identified, P1, was larger over the right posterior regions than the left posterior regions. P1 was reported in previous naming studies of words from French and English to be larger over the left posterior sites than the right homologues (e.g., Cohen et al., 2000; Grossi et al., 2001), regardless of the visual field in which the stimulus was presented (Cohen et al., 2000).[4] In con-

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[3] Note that there were missing data since the data of some participants did not have a peak within the specified 50 ms window in some conditions.

[4] This P1 effect is not inconsistent with the split fovea claim. The split fovea claim does not exclude any form of interhemispheric transfer; in contrast, it argues that the foveal representation is initially split and that each hemisphere plays a dominant role in the initial processing of the information in the visual hemifield to which it has direct access.
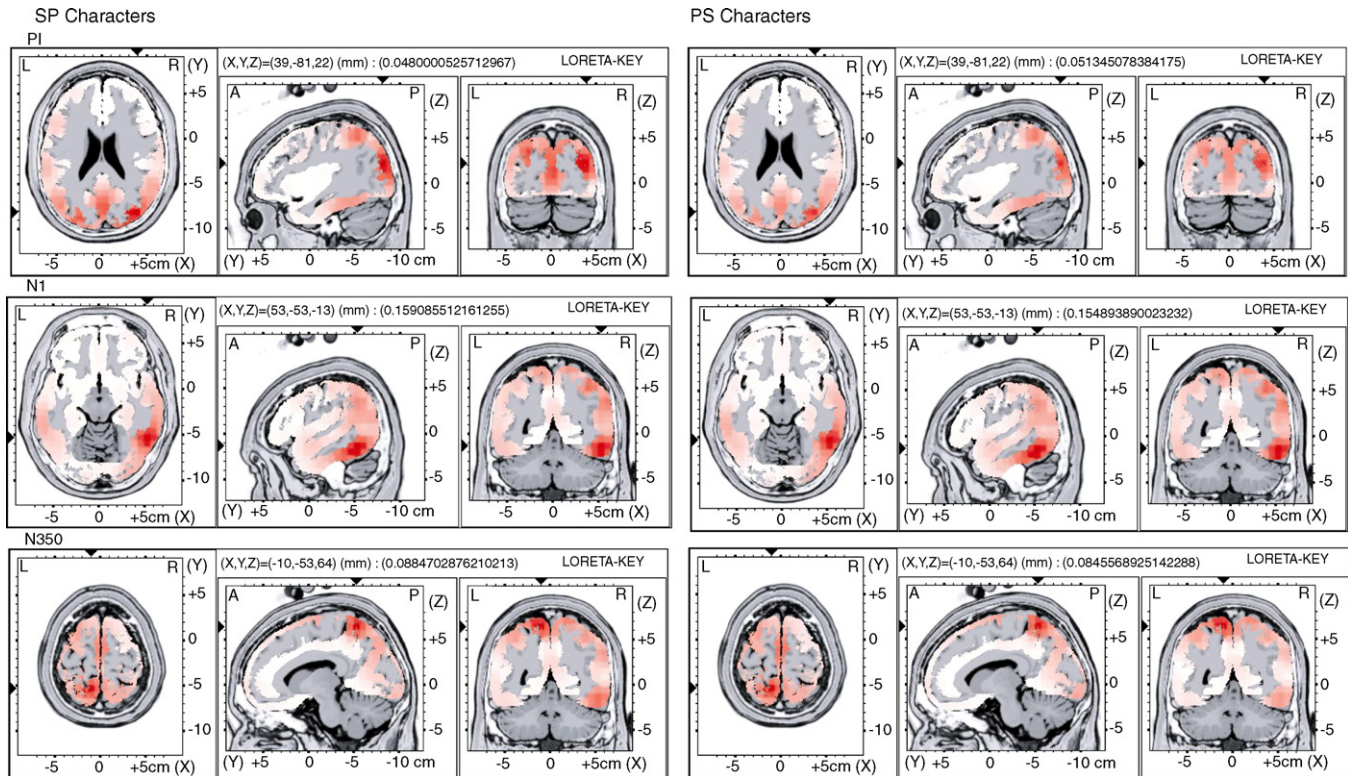
Fig. 9. Neuronal generator distribution of the three components identified at their peak latency. The figure shows the distribution for SP and PS character stimuli separately; the two types of stimuli had a similar distribution. Note that only raw data are displayed.

Table 1
The relevant clusters of the LORETA estimated source density distribution for each identified component

SP characters	Time after stimulus onset (ms)	Brodman area	Talairach coordinate	Maximal current density value
P1	128	BA19	[39, −81, 22]	0.048
	128	BA19	[−24, −81, 36]	0.040
N1	196	BA37	[53, −53, 13]	0.159
N350	334	BA7	[−10, −53, 64]	0.088
	334	BA37	[53, −53, 13]	0.040
PS characters	Time after stimulus onset (ms)	Brodman area	Talairach coordinate	Maximal current density value
P1	128	BA19	[39, −81, 22]	0.051
	128	BA19	[−24, −81, 36]	0.039
N1	196	BA37	[53, −53, 13]	0.155
N350	334	BA7	[−10, −53, 64]	0.085
	334	BA37	[53, −53, 13]	0.043

The selection of time windows was based on global field power data.

trast to studies of English word reading, previous fMRI and ERP studies of Chinese character recognition have generally exhibited a bilateral or more right-lateralized activation in the visual system (e.g., Chee, Tan, & Thiel, 1999; Liu & Perfetti, 2003; Tan et al., 2000, 2001). This pattern is attributed to the square shape and the visual complexity of Chinese characters, which demands elaborate visual/spatial analyses (Tan et al., 2001). The result obtained in the current study hence is consistent with the previ-

ous research.[5] The source localization data also showed that its estimated generator distribution was primarily centred on medial

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[5] Kutas, Van Petten, and Besson (1998) also reported P1 amplitude larger over the RH in a sentence reading task. Note, however, that the P1 amplitude observed in their study may have been influenced by the potentials elicited by all words in the sentences, and hence may be different from that observed in isolated word stimuli presentation.

occipital lobe (BA 19 and 18), with larger intensity in the RH (cf. Rossion et al., 2003). The non-significant interaction between character type and hemisphere in P1 suggested that in the neural activities reflected at this stage, the two types of characters may be processed in the same way by the two hemispheres, and hence no foveal splitting effect was observed. Nevertheless, the functional significance of P1 is still controversial. Sereno, Rayner, and Posner (1998) reported effects of "wordness" (alphabetic words versus non-words) in P1 in a lexical decision task, whereas Cohen et al. (2000) reported no difference between alphabetic words and non-words at this stage in a word naming task.[6] This inconsistency may be due to different tasks adopted. Rossion et al. (2003) suggested that P1 may reflect low-level visual properties, such as spatial frequency spectra, since in their study there was no difference observed in P1 between pictures of cars and faces, which had more comparable low-level visual features. Further investigation is required before drawing a definite conclusion.

4.1.2. N1

N1 was elicited at around 180–200 ms over the posterior ventral regions. N1 has been reported to have larger amplitude contralateral to the stimulus presentation, for both non-linguistic stimuli (Mangun, 1995) and word stimuli (e.g., Federmeier, Mai, & Kutas, 2005). For example, Cohen et al. (2000) reported that in the left posterior regions, right visual field (RVF) stimuli elicited larger N1 amplitude than left visual field (LVF) stimuli; the opposite pattern was observed in the homologous regions of the RH. They hence suggested that initial visual processing was confined to early visual areas contralateral to the stimulated visual hemifield. The corresponding fMRI data also exhibited tightly localized contralateral activations, with the coordinates coinciding with area V4 in previous PET or fMRI studies of early visual processing (e.g., Hasnain, Fox, & Woldorff, 1998; Zeki et al., 1991). V4 has been known to be related to color and form vision and shape processing (e.g., Rizzo, Nawrot, Blake, & Damasio, 1992; Schiller & Lee, 1991). Cohen et al. (2000) hence argued that, for early visual processing at this stage, which has been revealed as the N1 component in ERP studies, visual information in each hemifield is still processed by the contralateral hemisphere and has not reached a location-invariant processing stage yet. Nevertheless, both the linguistic and non-linguistic stimuli used in the previous ERP studies were presented off the foveal vision. It hence remains unclear about whether the same contralateral effects can also be observed in the foveal vision.

In the current study, characters were presented within the foveal vision. The results showed a significant interaction between character type and hemisphere: there was larger N1 amplitude measured for SP characters in the LH, compared with PS characters; an opposite pattern was observed in the RH. In Chinese orthography, the phonetic radicals usually have a more complicated structure with more strokes or stroke patterns than semantic radicals; in other words, the right of an SP character is usually more visually complex than the left, and the left of a PS character is usually more visually complex than the right. Hence, the interaction between character type and hemisphere observed here may have reflected the relative visual complexity between the left and right halves of the stimulus presented to the two hemifields, and suggested that the same contralateral effects in N1 amplitude may also be observed within the foveal vision. This phenomenon is consistent with the split fovea claim: a foveally presented stimulus is split about the fixation, with its two halves being initially contralaterally projected to different hemispheres and consequently eliciting different activations in the two hemispheres. Since such interaction between character type and hemisphere was not observed in the earlier component, P1, N1 was thus the earliest component in which the foveal splitting effect emerged in the current study.

In addition, N1 has been reported to be related to a discrimination process in an attended location (Vogel & Luck, 2000). In face recognition research, N1 (N170) has been reported to be larger for face stimuli compared with non-face objects; there is also a debate regarding whether this component is face-specific or due to our expertise to face recognition (e.g., Bentin & Carmel, 2002; cf. Schendan, Ganis, & Kutas, 1998). As mentioned above, because the phonetic radical types outnumber the semantic radical types in Chinese orthography, the information profile of SP characters is skewed to the right, whereas the information profile of PS characters is skewed to the left (Hsiao & Shillcock, 2006). Also, for SP characters, the phonologically important part of the characters, i.e., the phonetic radical, is on the right side of the character, whereas PS characters have it on the left. Thus, it is also possible that the interaction between hemisphere and character type observed in N1 amplitude reflected the informativeness of different parts (i.e., left or right radical) in the attended stimuli for discrimination/recognition. These different hypotheses are current under examination.[7]

The source localization data showed that the estimated neuronal generator distribution of N1 was lateralized to the fusiform gyrus and the inferior temporal gyrus in the RH (Fig. 9). The locations were consistent with previous ERP studies showing that the posterior fusiform gyrus is activated during visual processing of object, face, and word recognition around this time window (e.g., Rossion et al., 2003). Note, however, that in the current study the source distribution for Chinese character stimuli were lateralized to the RH, in contrast to the usually left-lateralized source distribution for word stimuli of alphabetic languages such as English words (see, e.g., Rossion et al., 2003).

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[6] One issue regarding the nonword/word difference is that a hemifield view of this difference may not be the same as a non-hemifield view for early processing. For example, in a hemifield view, the nonword "muld" may still elicit early lexical processing whereas the nonword "ldmu" may not, since the beginning and ending halves of the word "muld" are existing word beginning and ending, as opposed to the nonword "ldmu" (cf. Shillcock et al., 2000).

[7] N1 has also been reported to interact with word/character frequency (e.g., Liu and Perfetti, 2003; Sereno et al., 1998). Since character frequencies were matched between the SP and PS characters in the current study, we do not attribute the effects obtained here to character frequencies. Also, there is no interaction between character frequency and hemisphere reported in the previous studies. Hence, the effect obtained here was unlikely to be due to a character frequency bias.

This phenomenon suggests again that the visual processing of Chinese orthography involves more RH activation compared with that of alphabetic languages (e.g., Tan et al., 2001).

A similar interaction was also observed in the P200 component, which together with N1 may be the two directions of a dipole activity (cf. Rossion et al., 2003). Indeed, the source distribution during this time window was very similar to that of N1. P200 has been reported to be related to first syllable frequency of words, but not the whole word frequency, in visual lexical decision tasks in Spanish and German (e.g., Barber, Vergara, & Carreiras, 2004; Hutzler et al., 2004). The first syllable frequency of words being referred to in these studies may be considered as related to the lead neighbourhood size in the English lexical decision studies (Lavidor et al., 2004; Lavidor & Walsh, 2003); thus, according to the split fovea claim, the first syllable of words presented in isolation is likely to be initially projected to and processed in the LVF/RH. An inhibitory effect of high first syllable frequency in visual lexical access has been reported behaviourally in Spanish and German (Carreiras, Alvarez, & de Vega, 1993; Conrad & Jacobs, 2004) and shown to be reflected in a smaller P200 amplitude elicited by words with high first syllable frequency compared with words with low first syllable frequency in lexical decision tasks. The less positive P200 elicited by words with high first syllable frequency may have indicated a higher processing load due to activation of the competing syllabic neighbours (in the RH) (Carreiras et al., 1993; cf. Holcomb, O'Rourke, & Granger, 2002; Hutzler et al., 2004). Barber et al. (2004) argued that this syllable frequency effect could be associated with phonological processing of the stimulus and activation of lexical candidates, whereas Stenneken, Conrad, Goldenberg, and Jacobs (2003) suggested an orthographic locus of this effect. Note that if this effect reflects RH processing (since the first syllable is likely to be initially projected to and processed in the RH), it may tend to be associated with phonological processing only in the female brain, due to greater left-lateralization of phonological processing in the male brain.

The first syllable frequency effect regarding P200 amplitude reported previously did not interact with hemisphere (Barber et al., 2004; Hutzler et al., 2004). In contrast, in the current study, an interaction between character type and hemisphere in P200 amplitude was observed. The same as the interaction observed between character type and hemisphere observed in N1 amplitude, this interaction in P200 amplitude reflected differential processes involved in SP and PS character recognition. According to previous studies concerning the sensitivity of P200 to first syllable frequency, but not word frequency, in lexical decision tasks, the P200 observed in the naming task here might be related to orthographic/phonological processing of radicals. This claim is consistent with an ERP study of Chinese character recognition in a homophone judgement task conducted by Liu, Perfetti, and Hart (2003). Their results showed reduced P200 amplitude when the target and the prime characters shared a radical compared with a control condition and hence suggested the involvement of P200 in orthographic/phonological processing of radicals.

Thus, in the current study, SP characters elicited a larger N1 and a less positive P200 in the LH compared with the RH; in contrast, PS characters elicited a larger N1 and a less positive P200 in the RH compared with the LH. This interaction between character type (i.e., position of the phonetic radical) and hemisphere is consistent with the split fovea claim, suggesting that the two types of characters are processed differently in the brain because the semantic and phonetic radicals are initially projected to different hemispheres. Furthermore, the effects observed here suggest that the initial foveal splitting can reach far enough to influence phonological/orthographic processing of visual character/word recognition.

4.2. Late component: N350

The late component of interest, N350, has been reported to be related to phonological processing (e.g., Bentin et al., 1999; Fiez & Petersen, 1998; Grossi et al., 2001; Pammer et al., 2004). In the current study, a significant interaction between sex and character type was observed regarding N350 amplitude: in the male brain, PS characters elicited larger N350 than SP characters, whereas the pattern was reversed in the female brain. Drawing together the ERP data obtained here with the behavioural data in Hsiao and Shillcock (2005b), for males, PS characters elicited a larger N350 amplitude in the ERP data, and a longer response time to PS characters in the behavioural study, compared with SP characters, suggesting that PS characters may require more processing resources than SP characters in the male brain. In contrast, for females, there was a tendency in the other direction, suggesting that PS characters may be easier to process than SP characters, or a more equivalent processing of SP and PS characters in the female brain. The ERP data obtained here hence have provided substantial electrophysiological support for the observed interaction between character type and sex in the behavioural study, and have confirmed again that the effect of foveal splitting can extend far enough to interact with the sex of the reader in a relatively naturalistic reading task.

The source localization data showed that the estimated neuronal generator distribution of N350 was primarily centred on BA 7 in the left parietal lobe (Fig. 9). This location has also been reported by Lee et al. (2004) to be highly activated in an fMRI study of Chinese phonetic compound naming. They also showed that the left temporoparietal (BA 7/40), together with the left inferior frontal region, exhibited prominent character frequency and pronunciation consistency effects, and suggested that this region is responsible for the mapping between orthographic and phonological forms, possibly at the sublexical level, in reading Chinese phonetic compounds (see also Fu, Chen, Smith, Iversen, & Matthews, 2002; Tan et al., 2001). The source solution obtained here hence is consistent with previous fMRI studies of Chinese character pronunciation.

In conclusion, the ERP examination in the current study has provided electrophysiological evidence for foveal splitting effects in reading through a Chinese character recognition task. The interaction between hemisphere and character type observed in the peak amplitude of N1 and P200 was consistent with the split fovea claim. This effect was the earliest foveal splitting effect observed in the current study, and suggested that the effect of foveal splitting can reach far enough to influence

phonological/orthographic processing of visual character/word recognition. The interaction between sex and character type in N350 amplitude showed that the two character types are processed differently in the male and female brain. It has provided electrophysiological evidence for the sex differences in naming Chinese SP and PS characters observed in the behavioural study (Hsiao & Shillcock, 2005b), and confirmed again that the effect of foveal splitting can extend far enough to interact with the sex of the reader in a relatively naturalistic reading task.

Acknowledgments

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