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An early electrophysiological response associated with expertise in letter perception

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Abstract

Expertise with print is likely to optimize visual processes for recognizing characters of a familiar writing system. While brain activations have been identified for words and letter strings compared to other stimuli, relatively little work has focused on the neural basis of single letter perception. English readers and Chinese-English bilinguals participated in an ERP study and performed a 1-back identity judgment on Roman letters, Chinese characters, pseudofonts, and their string versions. The Chinese-English bilinguals showed an enhanced N170 for both Roman letters and Chinese characters compared to pseudofonts. For the non-Chinese readers, the N170 amplitude was larger for Roman letters relative to Chinese characters and pseudofonts. Our results suggest that changes in relatively early visual processes underlie expert letter perception.

Perceptual expertise with letters is one of the results of our prolonged experience with print and reading. The extensive reading experience taking place over the years after we become literate likely modifies the way we process and perceive individual letters. For instance, expert readers are used to seeing print in a coherent style, and are thus able to extract font information to aid letter recognition. They perform a letter identification task better with letter strings of the same font than of mixed fonts (Sanocki, 1987, 1988). Novice readers (e.g., English readers viewing Chinese characters), however, are not as efficient in using this font information (Gauthier, Wong, Hayward, & Cheung, submitted). Likewise, expert readers are accustomed to seeing letters in the context of words. When they fixate on a part of a word, they obtain not only high-resolution information of the letters in the fovea but also low-resolution information of the parafoveal letters. With experience they develop a strong tendency to use low-resolution information of the parafoveal letters, such that even when high-resolution information is artificially made available (by magnifying the parafoveal letters), the readers are unable to utilize this extra information (Nazir, Jocobs, & O'Regan, 1998). Such behavioral phenomena suggest that our perception of letters is influenced by our reading experience.

Neural selectivity can develop as a result of perceptual expertise with certain categories of objects (Gauthier, 2000). There are two neural hallmarks of the kind of expertise we acquire with identifying objects within homogeneous classes (e.g., faces, cars, dogs, birds, and computer-generated novel objects). Compared with common objects these objects of expertise elicit a larger event-related potential (ERP) component, N170, in posterior brain regions (Rossion, Gauthier, Goffaux, Tarr, & Crommelinck, 2002; Tanaka & Curran, 2001), and greater recruitment of a small region in the fusiform gyrus, mainly on the right (Gauthier, Skudlarski, Gore, & Anderson, 2000; Gauthier, Tarr, Anderson, Skudlarski, & Gore, 1999). Because the kind of expertise we have with letters differs in several ways from the kind of expertise we have with faces, cars or dogs, letters would be expected to recruit a different part of the extrastriate cortex. Indeed, as described below, words and letterstrings (Cohen et al., 2002; Polk & Farah, 1998) and more recently single letters (James, James, Jobard, Wong, & Gauthier, submitted) elicit greater activity in parts of the left fusiform gyrus compared to control stimuli, including digits and unfamiliar characters. ERPs would also be expected to reveal this neural selectivity for letters, and there is in fact some evidence for an early selective response for letters, although the emphasis has been on higher-level stimuli such as words (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999).

The majority of neural studies about print have focused on selectivity to words and pronounceable strings (Assadollahi & Pulvermuller, 2003; Bookheimer, 2002; Cohen et al., 2000; Cohen et al., 2002; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; Hauk & Pulvermuller, 2004; McCandliss, Posner, & Givon, 1997; Petersen, Fox, Snyder, & Raichle, 1990; Proverbio, Vecchi, & Zani, 2004). These studies therefore address the linguistic more than the perceptual aspect of reading. More relevant to the question of neural selectivity for letters *per se* are studies showing more activity for unpronounceable letter strings than control stimuli. For example, the amplitude of the N170 is greater for words, pseudowords, and unpronounceable consonant strings than for strings formed by alphanumeric symbols and forms (Bentin et al., 1999). A greater P150 component has also been found not only for words and letter strings, but also for strings of letter-like stimuli, compared with object icon strings (Schendan, Ganis, & Kutas, 1998). The P150, maximal at the central top electrode (Cz) when recorded with respect to a mastoid reference, may be the positive counterpart of the N170 maximal at occipito-temporal electrodes. A larger intracranial N200 has also been found bilaterally in the posterior fusiform gyrus for words and nonwords (pronounceable or not) compared with objects like cars and butterflies (Allison, McCarthy, Nobre, Puce, & Belger, 1994; Nobre, Allison, & McCarthy, 1994). An fMRI study showed more activity for letter strings than textures and faces at the left occipito-temporal junction (Puce, Allison, Asgari, Gore, & McCarthy, 1996). Greater fMRI activations have also been found for letter strings than digit strings in a widespread area around the left fusiform gyrus (Polk et al., 2002). These results suggest neural selectivity for strings of letters and letter-like stimuli that do not readily contain linguistic information at a word level.

One may intuitively equate the selectivity for unpronounceable strings to selectivity for letters, although this is not necessarily correct for two reasons. First, since letter strings are more word-like perceptually, they are likely to evoke more word-level processes involving orthography, phonology, etc., than single letters (Price, 2000). Second, an interesting dissociation has been obtained between two areas in the occipito-temporal region, one being selective for individual letters but not for letter strings, with the other being selective for strings but not individual letters (James et al., submitted).

A few other studies suggested selectivity for individual letters. For example, fMRI activity in bilateral occipito-temporal areas habituates to the same letter in the same font (vs. different fonts) but not to the same face (vs. different faces) (Gauthier, Tarr et al., 2000). Also, there is more fusiform gyrus activity for single letters than oblique lines (Longcamp, Anton, Roth, & Velay, 2003). More left middle occipital activations have also been shown for single letters compared with symbols and colors (Flowers et al., in press; Garrett et al., 2000). A concern is that these fMRI activations may be caused by feedback from higher-level processing, e.g., letter naming. However, a number of MEG studies by Tarkiainen and colleagues argue against this alternative account (Tarkiainen, Cornelissen, & Salmelin, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). They located a left inferior occipito-temporal region showing more activity at about 150 ms for pronounceable letter strings than for strings of rotated letters. Despite the primary interests of the authors on strings, this region also showed more activity for single upright letters than rotated ones. The early latency of these MEG responses make the feedback from higher-level processes a less likely explanation for the selectivity found in above-mentioned fMRI studies.

The current study examines the early neural selectivity associated with letter expertise. Two groups of participants (English readers who cannot read Chinese, and Chinese-English bilinguals) took part in an ERP experiment and saw three types of characters (Roman, Chinese, pseudofont). The Group × Stimulus Type design creates expert (non-Chinese readers viewing Roman characters, bilinguals viewing Roman and Chinese characters) and novice situations (non-Chinese readers viewing Chinese and pseudofont characters, bilinguals viewing pseudofont characters), allowing a more direct test of the association between expertise and neural selectivity for letters. For example, the same stimuli (Chinese characters) were expected to elicit different levels of activity depending on the amount of expertise, i.e., bilinguals were expected to show comparable activity with Roman letters and Chinese characters, while non-Chinese readers were expected to show more activity with Roman letters than Chinese characters. Such results would not be explained by the feature differences between the stimuli, which are difficult to control perfectly. The use of both alphabetic and logographic characters also improves the generalizability of results.

We adopted ERPs to tap into early, visual letter processing relatively isolated from most linguistic processes. Past research shows that the earliest potential reflecting high-level, visual differences among object categories appear as a posterior negative component peaking at about 170 ms after stimulus presentation (Bentin, Allison, Puce, Perez, & et al., 1996; Curran, Tanaka, & Weiskopf, 2002; Rossion, Gauthier et al., 2002; Tanaka & Curran, 2001). This N1/N170 potential has been shown to be highly associated with expertise level, among other factors (Gauthier, Curran, Curby, & Collins, 2003; Rossion, Gauthier et al., 2002; Tanaka & Curran, 2001). Therefore, we expected a larger N170 (compared with pseudofont control) at posterior channels for letters of expertise, i.e., Roman letters for non-Chinese readers, and both Roman letters and Chinese characters for bilinguals. It is important to note that any N170 effect for letter expertise would not necessarily reflect the same processes as the N170 effect found for subordinate-level object and face expertise. Since various spatio-temporally overlapping visual processes are likely to contribute to the scalp-recorded N170 (Rossion, Curran, & Gauthier, 2002), it is a reasonable postulate that the N170 can be modulated by different types of perceptual expertise with objects. Our primary aim here is not to equate or dissociate letter expertise from face-like expertise, but to describe properties of the selectivity associated for letters and letter-strings with expertise.

Method

Participants

Thirty-seven undergraduates from University of Colorado at Boulder participated for course credit. Twenty-two Chinese-English bilinguals participated for payment of $15/hour. Because we were unable to recruit as many bilingual subjects, the present results included only 18 non-Chinese readers and 18 Chinese-English bilinguals. Subject selection was based upon absence of EEG artifact (6 monolingual and 1 bilingual subjects were excluded for excessive artifact), maintaining high accuracy levels and minimizing group differences in accuracy (subjects with less than 90% accuracy were excluded: non-Chinese = 6, Chinese-English = 3), maintaining counterbalancing, and equating the sex distribution of the two groups (9 males and 9 females per group). The Chinese-English bilinguals, who were mostly graduate students, were older (MN = 24, range = 19 - 29) than the undergraduate non-Chinese readers (MN = 19, range = 18 - 22). All of the Chinese-English bilinguals were born in China, learned English in China (mean age = 11, range = 4 to 15), had known English for a long time (mean years = 13, range = 5 to 21), and recently moved to the US (mean years in US = 3, range = 1 to 10).

Stimuli, design, and procedure

There were six types of stimuli (Roman, Chinese, and pseudofont characters, and their string versions). Figure 1 shows the eight Roman consonants, eight Chinese characters, and eight pseudofont characters used, and one example of each type of trials. Each character was about 1 $\times$ 1 cm large (0.57 degree at a viewing distance of 100 cm). Each string consisted of 5 characters and was about 7 cm wide (4 degree at a viewing distance of 100 cm). The Roman strings were formed by first randomly picking and assembling Roman letters to form 100 different 5-character strings, and then replacing characters for certain strings according to the following rules: (a). There is no repetition of letters within each string. (b). All letters occur at approximately the same frequency in the 100 strings (mean = 62; range = 58-65). (c). All letters occur at approximately the same frequency in the central, underlined position (12 or 13). (d). There are no familiar or potentially meaningful 2-letter character combinations (e.g., HP, HB, BP, HK). (e). There are no valid graphemes (e.g., BL, PH). (f). All 2-letter combinations (e.g., “DF”), except the removed ones, occur at similar frequencies (mean = 7.96; range = 6-12). The Chinese and pseudofont strings were formed by taking the 100 Roman strings and replacing them with the corresponding Chinese or pseudofont characters. We also checked to ensure that there was no meaningful character combination in Chinese strings (e.g., 干土, which means “dry soil”).

Figure 1 inserted here

There were 100 trials for each of the six types of stimuli, separated into 5 blocks, each containing 20 trials. Participants performed a 1-back identity-matching task. Each trial started with a fixation cross at the center for a random period between 250 and 750 ms. A stimulus (a character or string) then appeared for 750 ms, followed by a 500-ms blank screen, and the fixation for the next trial. Participants were instructed to press the key “1” on the number key pad when the character shown was identical to the previous one, or when the central, underlined character of the current string repeated that of the previous string (flanking characters were always different in both same and different trials). These “same” trials amounted to 10% of all trials for each stimulus (i.e., 10 out of 100). The numbers of same trials were 1, 2, 2, 2, and 3 for the five blocks. The six types of stimuli formed a total of 600 trials presented in 30 blocks. Each block only contained one type of stimuli. The different stimulus blocks alternated with each other, such that the six types of stimulus blocks were each presented once before any one of them was presented the second time, and so on. The order of block presentation was counterbalanced across participants. Forty trials (20 for Roman letters, 20 for Roman strings) were introduced at the beginning as practice.

EEG/ERP methods

Scalp voltages were collected with a 128-channel Geodesic Sensor Net™ (Tucker, 1993) connected to an AC-coupled, 128-channel, highinput impedance amplifier (200 MΩ, Net Amps™, Electrical Geodesics Inc., Eugene, OR). Amplified analog voltages (0.1-100 Hz bandpass, -3 dB) were digitized at 250 Hz. Individual sensors were adjusted until impedances were less than 50 kΩ. The EEG was digitally low-pass filtered at 40 Hz. Trials were discarded from analyses if they contained incorrect responses, eye movements (EOG over 70 μV), or more than 20% of channels were bad (average amplitude over 100 μV or transit amplitude over 50 μV). The mean number of trials per subject per condition was 90 (range = 63 to 100). Individual bad channels were replaced on a trial-by-trial basis with a spherical spline algorithm (Srinivasan, Nunez, Silberstein, Tucker, & Cadusch, 1996). EEG was measured with respect to a vertex reference (Cz), but an average-reference transformation was used to minimize the effects of reference-site activity and accurately estimate the scalp topography of the measured electrical fields (Bertrand, Perin, & Pernier, 1985; Curran, Tucker, Kutas, & Posner, 1993; Dien, 1998; Lehman & Skrandies, 1985; Picton, Lins, & Scherg, 1995; Tucker, Liotti, Potts, Russell, & Posner, 1994). Average-reference ERPs were computed for each channel as the voltage difference between that channel and the average of all channels. The average reference was corrected for the polar average reference effect (Junghöfer, Elbert, Tucker, & Braun, 1999).

ERPs were baseline-corrected with respect to a 100-ms prestimulus recording interval.

Results

Both groups of subjects maintained a high level of accuracy: non-Chinese readers = 96%, Chinese-English Bilinguals = 97%, $t(34) = 1.44$, $SE = .81$, $p > .10$.

ERPs from selected 10-20 locations are show in Figures 2 (non-Chinese readers viewing characters), 3 (non-Chinese readers viewing strings), 4 (Chinese-English bilinguals viewing characters), and 5 (Chinese-English bilinguals viewing strings). Overall, the most outstanding feature is the P300 difference related to expertise (e.g., channel Pz between about 300 and 600 ms). P300 amplitude was smaller when subjects viewed stimuli with which they had experience (non-Chinese readers viewing Roman stimuli, bilinguals viewing Roman or Chinese stimuli) than when they viewed unfamiliar stimuli (non-Chinese readers viewing Chinese or pseudofont stimuli, bilinguals viewing pseudofont stimuli). Presumably, unfamiliar characters and strings were perceptually more complex, and P300 amplitude is known to increase with stimulus complexity (Johnson, 1986, 1993). Given our interest in early visual processes, formal analyses focused on earlier N170 effects.

Figures 2-5 inserted here

The first step in our analysis was the identification of the locations where the N170 component was maximal, so that further analyses could focus on these channels. For each subject, we computed the amplitude of the most negative deflection occurring over all posterior electrode sites between 120 and 250 ms after stimulus onset. Averaging over all subjects and conditions, the N170 was most negative at left-hemisphere channel 65 (falling between standard 10-20 locations T5 and 01, see Figure 6). To allow for spatial variability across subjects and conditions, we selected a group of channels surrounding 65 for further analysis (T5, 59, 64, 65, 66, 70, O1) along with their right-hemisphere counterparts (02, 85, 90, 91, 92, 96, T6). The ERPs obtained by averaging the channels within each region are shown in Figures 7 (non-Chinese readers) and 8 (Chinese-English bilinguals).

Figures 6-8 inserted here

The latency of the minumum N170 was entered into a Group (non-Chinese, Chinese-English bilingual) x Stimulus (Chinese, Roman, pseudofont) x Character/String x Hemisphere analysis of variance (ANOVA). When necessary in this and all subsequently reported ANOVAs, degrees of freedom were adjusted according to the conservative Geisser-Greenhouse procedure for sphericity violations (Winer, 1971). The N170 was faster over the left (mean = 175 ms) than right hemisphere (mean = 182 ms), $F(1, 34) = 10.63$, MSE = 526.10, $p < .01$; faster for strings (mean = 176 ms) than characters (mean = 181 ms), $F(1, 34) = 5.80$, MSE = 441.93, $p < .05$; and these factors interacted such that the latency difference between characters and strings was only significant over the left hemisphere, $F(1, 34) = 7.05$, MSE = 132.53, $p < .05$. The Group x Stimulus x Hemisphere interaction was also significant, $F(1, 34) = 3.25$, MSE = 80.08, $p < .05$. The interactions suggested that latency differences between stimulus types were ordered Roman < pseudofont < Chinese over the left hemisphere of Chinese-English bilinguals and the right hemisphere of non-Chinese readers, but ordered Chinese = Roman < pseudofont over the right hemisphere of Chinese-English bilinguals and the left hemisphere of non-Chinese readers. Across the 12 conditions comprising this interaction, the mean latencies ranged from 171 to 186 ms, so the latency differences were not large in magnitude.

Previous N170 studies have used mean amplitude as the primary dependent measure, but minimum amplitude was used for the present analysis for two primary reasons. First, latency differences between conditions may bias the results if a fixed window is used for calculating mean amplitude. Second, inspection of the ERPs suggested that expertise-related Group x Stimulus interactions were also observed in the P300 component starting around 200 ms, so we were unable to select a N170 mean-amplitude window that did not overlap with the P300.

Minimum amplitude was entered into a Group (non-Chinese, Chinese-English bilinguals) x Stimulus (Chinese, Roman, pseudofont) x Character/String x Hemisphere ANOVA. All significant (p <. 05) results are reported in Table 1. Overall N170 amplitudes were more negative for the bilingual than non-Chinese subjects. The key result was the significant Group x Stimulus interaction (Figure 9). For non-Chinese subjects, the N170 to the Roman stimuli was more negative than to the Chinese or pseudofont stimuli (both *ps* < .01, based on simple effects tests). For bilingual subjects, the N170 to both the Roman ($p < .05$) and Chinese ($p < .01$) stimuli was more negative than to pseudo stimuli. Thus, the N170 was modulated by expertise. The Group x Character/String interaction suggested that the string/character difference was greater for the bilingual than non-Chinese participants. Because of the Group x Stimulus interaction, the other interactions involving the stimulus variable can be more meaningfully interpreted with separate ANOVAs for each group (below).

Table 1 inserted here

Figure 9 inserted here

The non-Chinese subjects were considered alone in a Stimulus (Chinese, Roman, pseudofont) x Character/String x Hemisphere ANOVA. Only the stimulus condition effect described previously was significant. Considering the Chinese-English bilinguals alone, the stimulus condition effect was again significant. The Stimulus x Hemisphere interaction suggested that these condition effects were more pronounced over the left hemisphere. Also, the N170 was significantly more negative to strings than to characters.

A principal components analysis (PCA), using Dien's PCA Toolbox (available from jdien@ku.edu), was performed to determine if our initial

N170 analyses could be replicated within an independent analytic technique. A temporal PCA was calculated from -100 to 896 ms with 27864 observations per time point (36 subjects x 6 conditions x 129 channels = 27864). We used a covariance matrix as the measure of association, Kaiser normalization, and promax rotation (Dien, Beal, & Berg, submitted). A scree test indicated that 19 factors should be retained (accounting for 86% of the variance), seven of these factors each accounted for at least 10% of the variance. Subsequent analyses focused on a temporal factor, accounting for 12% of the variance, that peaked at 160 ms and was maximal at channel 65 because its timing and location were consistent with the N170 (see Figure 10, upper left).

The factor scores from the "N170 factor" were entered into a Group x Stimulus x Character/String ANOVA. As in the original analysis, the Group x Stimulus interaction was significant, $F(2, 68) = 3.93$, MSE = 1.24, $p < .05$. As shown in Figure 10 (bottom, left), the form of this interaction was similar to that shown in the original analysis of minimum amplitudes (Figure 9), in that the amplitude of the N170 factor varied with expertise.

Next, the N170 temporal factor was further decomposed with a spatial PCA. Five spatial factors were retained. Of these, only a single left-posterior factor (peaking at channel 65) appeared to be influenced by expertise (see Figure 10, right). The resultant Group x Stimulus interaction on the factor scores was marginally significant, $F(2, 68) = 2.87$, MSE = 1.30, $p = .06$. Thus, the activity recorded over the left hemisphere appeared to make the largest contribution to the N170 expertise effects identified in the PCA.

Figure 10 inserted here

In addition to the N170 temporal factor, a temporal factor peaking at 448ms appeared related to the P300 (accounting for 48% of the temporal PCA variance). Spatial PCA decomposition of this P300 factor showed that a single parietally maximal factor (peaking at channel 78) captured the apparent expertise effect on the P300 that is evident from Figures 2 through 5 (channel P4). The Group x Stimulus interaction showed that the P300 amplitude within each group was higher for unfamiliar stimuli, $F(1, 34) = 5.01$, MSE = .52, $p < .01$.

Discussion

To our knowledge, this is the first study showing selectivity of the N170 component to individual letters associated with expertise. The current results are consistent with and complement previous findings in several ways. First, a larger N170 was shown for Roman letters than pseudofont characters for all participants. This early component, selective for individual letters and letter strings, suggests that the selectivity found in other fMRI studies (Flowers et al., in press; James et al., submitted; Longcamp et al., 2003) were not solely caused by feedback from higher-level areas related to linguistic processing or letter name knowledge. Second, the Group × Stimulus design in our study bypassed the problem of choosing a well-designed control stimuli. We found that the same Chinese characters resulted in either a smaller N170 amplitude than the Roman letters (in non-Chinese readers) or a comparable amplitude (in the Chinese-English bilinguals), depending on whether one was experienced with the Chinese characters or not. This expertise-associated letter selectivity cannot be explained by stimulus differences. Third, the use of Chinese characters enables us to generalize our results to logographic characters in a very different writing system. Fourth, the present results with letters demonstrate expertise effects on the N170 that are similar to expertise effects previously demonstrated with objects (Gauthier et al., 2003; Rossion, Gauthier et al., 2002; Tanaka & Curran, 2001). Last, the stronger expertise effect in the left hemisphere, as suggested in the PCA analyses and the Stimulus x Hemisphere interaction on N170 amplitude in the Chinese-English bilinguals, is consistent with Tarkiainen et al.'s

(Tarkiainen et al., 2002; Tarkiainen et al., 1999) finding of left-hemisphere preponderance of letter and letter-string selectivity.

Letter expertise and linguistic effects

The neural selectivity we found for individual letters is unlikely to reflect in a direct fashion language-related processes at the word level or at the level involving multiple letters. Different ERP components have been shown to be sensitive to information at the word level, such as orthography (McCandliss et al., 1997; Proverbio et al., 2004), phonology (Bentin et al., 1999), and semantics (Bentin et al., 1999; McLaughlin, Osterhout, & Kim, 2004). However, the early N170 selectivity we found for individual letters is likely to be free from these linguistic effects, because (a) the linguistic factors typically have a late effect occurring after 300 ms (except for the lexical frequency and orthography effects discussed below); and (b) we showed selectivity with single Roman letters, that supposedly do not contain linguistic information involving a word or multiple letters. There remains a possibility that the selectivity we found, at least for Chinese characters, reflects linguistic processing at a character level. For example, Perfetti and colleagues (Perfetti & Tan, 1998) found that orthographic and phonological processing started with individual Chinese characters within 100 ms after stimulus presentation. However, in their recent ERP study (Liu & Perfetti, 2003), the phonological processing component found for Chinese characters did not appear until 400 ms after stimulus onset.

It is worth mentioning that some linguistic factors, like lexical frequency and orthography, do have an effect on early ERP components (Hauk & Pulvermuller, 2004; McCandliss et al., 1997; Proverbio et al., 2004; Sereno, Brewer, & O'Donnell, 2003; Sereno, Rayner, & Posner, 1998). Lexical frequency is particularly interesting, since it apparently contradicts our expertise effect. Studies found a larger N1/N170 for low-frequency than high-frequency words (Hauk & Pulvermuller, 2004; McCandliss et al., 1997; Proverbio et al., 2004; Sereno et al., 2003; Sereno et al., 1998). Interestingly our results show a larger N170 for the more familiar, expert letters than non-expert letters. It has been suggested that the higher difficulty of processing low-frequency than high-frequency words may lead to the larger N1 for the low-frequency words (Sereno et al., 2003). In that case, words of different frequencies utilize the same neural substrates. The situation may be different in this study. Expert and non-expert letters may be treated as different types of stimuli, potentially by partly dissociable neuronal ensembles. The larger N170 for letters of expertise may indicate that additional substrates are recruited for them.

Letter expertise and subordinate-level expertise

Past studies have shown a greater N170 for faces than for other common objects (Bentin et al., 1996; Rossion et al., 2000). Enhanced N170 components have also been observed when people develop expertise with other objects like cars, dogs, birds, and even novel objects (Curran et al., 2002; Rossion, Gauthier et al., 2002; Tanaka & Curran, 2001). The current results generalize this effect to another stimulus domain – individual letters. One question is whether the same processes underlie the expertise with letters and other categories of objects. The process-map hypothesis of cortical organization provides a framework for considering this question (Gauthier, 2000). According to this hypothesis, one develops neural selectivity to an object class after prolonged experience of processing the objects in a specific manner. In other words, the specific neural selectivity is related to the specific constraints of the task associated with the category. Following this logic, letter expertise may be regarded as different from the other "subordinate-level" expertise studied before, because different computational demands are involved. To perceive letters during reading, one needs to perceive a particular letter as, for instance, a "g" and not an "f", irrespective of any subordinate-level differences like font, size, color, etc. For faces and many other categories of expertise, however, people usually gain experience in discriminating among very similar objects of a homogeneous class (e.g., telling one face from the other, or distinguishing between two different bird species). It is thought that the resulting expertise relies on holistic and configural processes (Diamond & Carey, 1986). The N170 component has recently been associated with holistic processing in car experts (Gauthier et al., 2003). This difference in task demands suggests that letter expertise may not be readily included as an example of the subordinate-level expertise. Different neural and behavioral phenomena may thus be found for these two types of expertise. Indeed the two types of expertise seems to be supported by different neural substrates as shown in an fMRI study (Gauthier, Tarr et al., 2000).

While the above question is worth pursuing, it should be noted that distinguishing the expertise for letters from the expertise we have with faces is not the purpose of this study, especially given the limited spatial resolution of the ERP technique. In fact, we did not find any significant differences between individual letters and letter strings in terms of the topography of their activations, despite the different loci of letter- and string-selective regions shown in recent fMRI results (James et al., submitted). We can only conclude that the visual processing associated with expertise for letters, letter-strings, faces as well as other objects of expertise (e.g., birds, dogs or cars) appears to occur within the same time window.

Up to now, single letter recognition has not been the focus of reading or object recognition studies, but our results suggest that it may be an important avenue for future explorations. Psychophysical studies argued that performance in word recognition depends on how well individual letters are identified (Nazir et al., 1998; Pelli, Farell, & Moore, 2003). Some studies of pure alexia have linked the reading disorder to deficits in letter recognition (Arguin, Fiset, & Bub, 2002; Saffran & Coslett, 1998). Accordingly, understanding letter recognition is one important step in understanding the reading process. In addition, the perception of letters distinguishes itself from the perception of other shapes and objects, as indicated by some unique behavioral phenomena (Gauthier et al., submitted; Sanocki, 1987, 1988). The present study provides another source of support for the uniqueness of individual letter perception, with evidence for early neural selectivity for familiar individual letters. In the future, efforts to compare processes and neural substrates supporting the perception of letters, common objects, and objects of subordinate-level expertise (like faces) should further our understanding of visual object recognition and how it changes when we acquire expertise in various domains.

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Table 1: N170 ANOVA Results

Effect	df	*F*	MSE	*p*
Both Groups				
Group	1, 34	9.84	44.18	< .01
Stimulus (Stim)	2, 68	12.04	1.23	< .001
Group x Stim	2, 68	7.05	1.23	< .01
Character/String (CR/ST)	1, 34	20.61	2.77	< .001
Gp x CR/ST	1, 34	4.61	2.77	< .05
Stim x Hemisphere	2, 68	3.54	0.39	< .05
Stim x CR/ST x Hemisphere	2, 68	4.15	0.18	< .05
Non-Chinese readers				
Stimulus (Stim)	2, 17	11.22	1.51	< .001
Chinese-English Bilinguals				
Stimulus (Stim)	2, 17	6.85	0.94	< .01
Character/String (CR/ST)	1, 17	24.31	2.55	< .001
Stim x Hemisphere	2, 34	3.91	0.35	< .05

Figure Captions

Figure 1. All the stimuli used in the experiment, as well as one example of each type of trial.

Figure 2. The ERPs from selected 10-20 locations for non-Chinese readers viewing characters.

Figure 3. The ERPs from selected 10-20 locations for non-Chinese readers viewing strings.

Figure 4. The ERPs from selected 10-20 locations for Chinese-English bilinguals viewing characters.

Figure 5. The ERPs from selected 10-20 locations for Chinese-English bilinguals viewing strings.

Figure 6. The channels selected for analyses (black).

Figure 7. The ERPs from averaging the selected channels for non-Chinese readers.

Figure 8. The ERPs from averaging the selected channels for Chinese-English bilinguals.

Figure 9. The average of minimum N170 amplitudes. Error bars show the standard error of the Chinese-pseudo and Roman-pseudo differences.

Figure 10. PCA results related to the N170. Left: The N170 factor identified with temporal PCA peaked at 160 ms over channel 65.

The topographic map shows the spatial distribution of the factor, calculated by multiplying the factor loadings by the factor scores and then by the standard deviations for the original data. Variation in the magnitude of the N170 factor across conditions is shown by plotting mean factor scores below. Right: Topography and factor score means for the left-hemisphere spatial component obtain through spatial PCA performed on the N170 temporal factor.

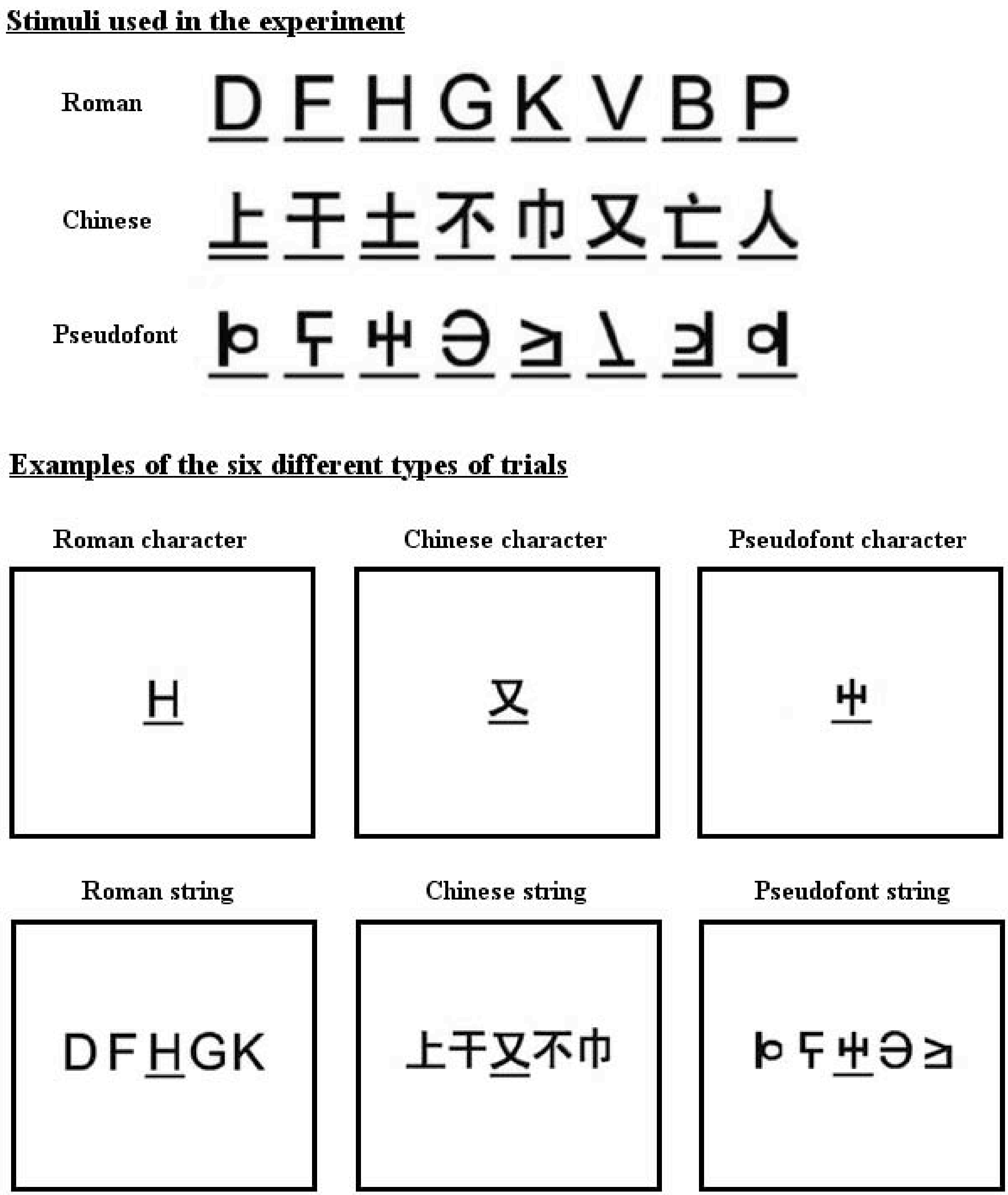
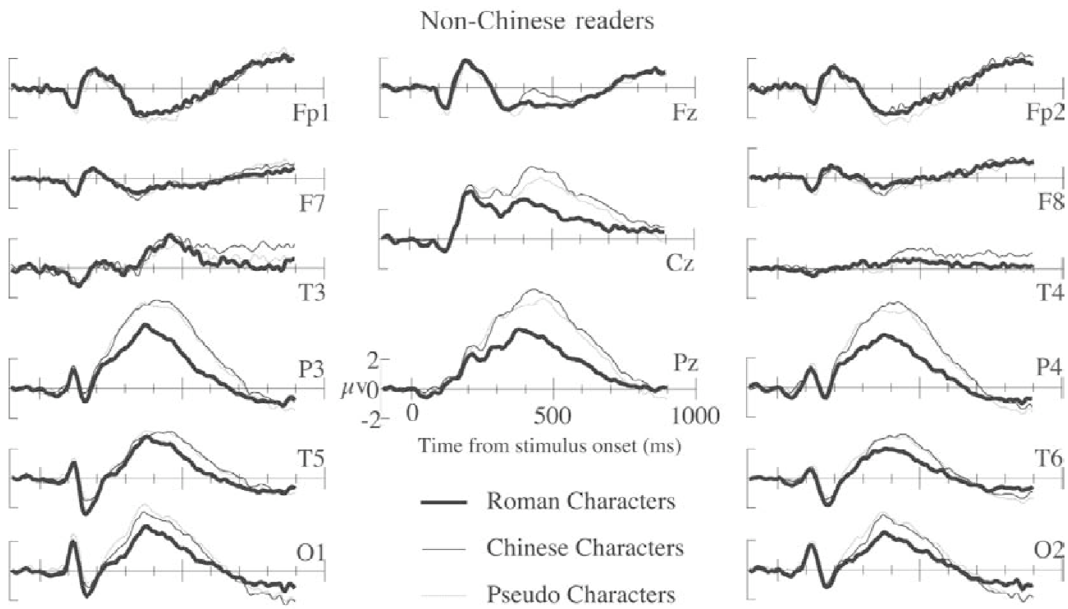

Stimuli used in the experiment
Roman
D F H G K V B P
Chinese
上 干 土 不 巾 又 亡 人
Pseudofont
Examples of the six different types of trials
Roman character
H
Chinese character
又
Pseudofont character
Roman string
DFHGK
Chinese string
上干又不巾
Pseudofont string

Figure 1



Non-Chinese readers
Fp1
Fz
Fp2
F7
F8
Cz
T3
T4
P3
Pz
P4
2
μv0
-2
0
500
1000
Time from stimulus onset (ms)
T5
T6
O1
O2
Roman Characters
Chinese Characters
Pseudo Characters

Figure 2

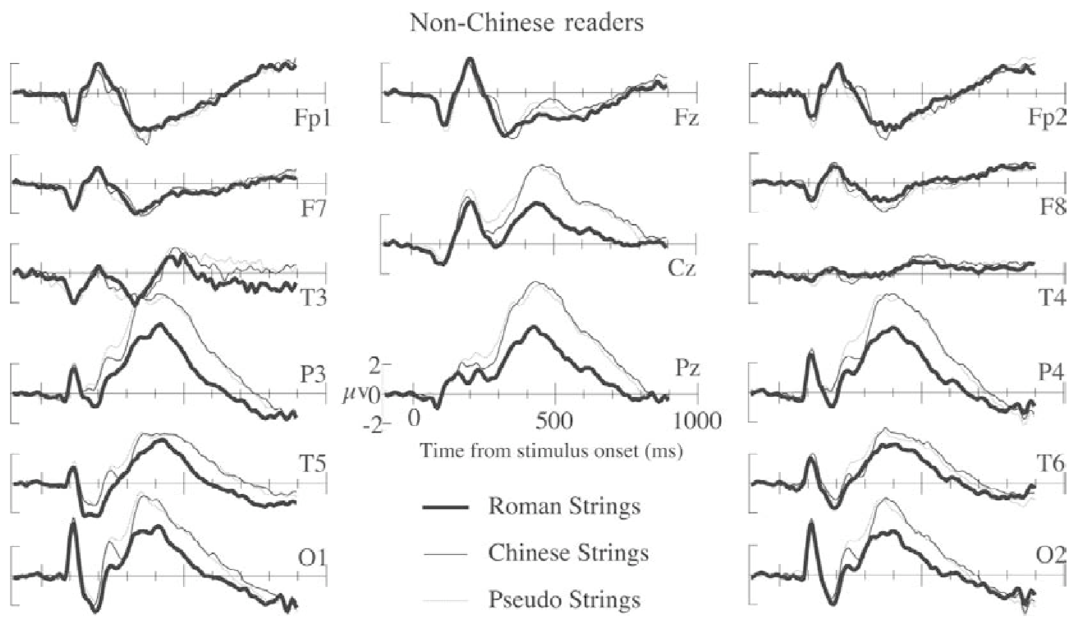

Non-Chinese readers
Fp1
Fz
Fp2
F7
F8
Cz
T3
T4
P3
Pz
P4
2
μv0
-2
0
500
1000
Time from stimulus onset (ms)
T5
T6
O1
O2
Roman Strings
Chinese Strings
Pseudo Strings

Figure 3

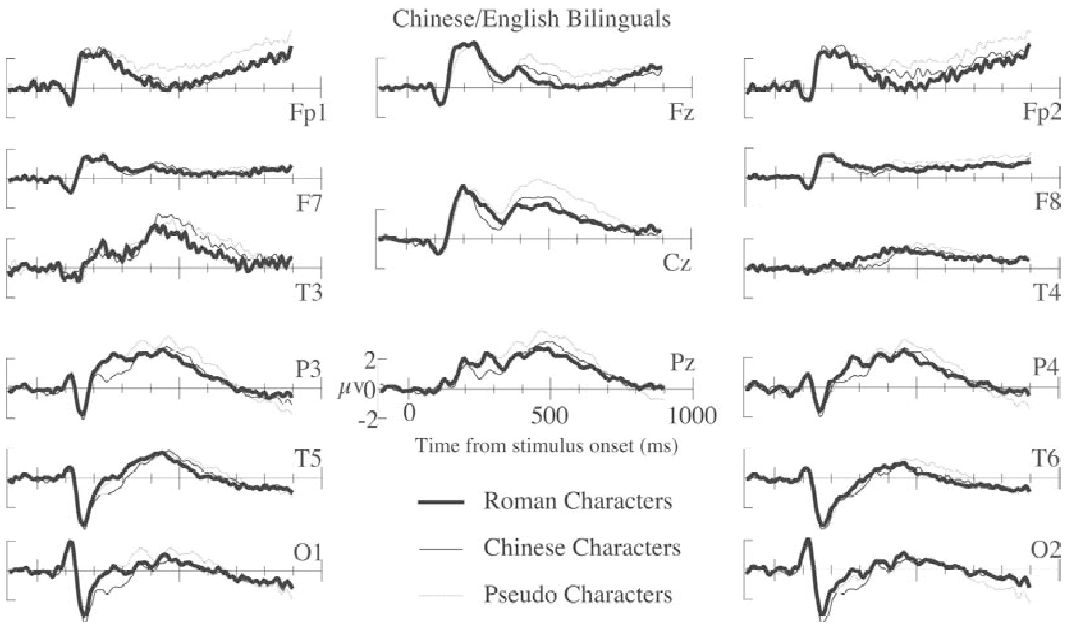

Chinese/English Bilinguals
Fp1
Fz
Fp2
F7
F8
T3
Cz
T4
P3
Pz
P4
2
μv 0
-2
0
500
1000
Time from stimulus onset (ms)
T5
T6
O1
O2
Roman Characters
Chinese Characters
Pseudo Characters

Figure 4

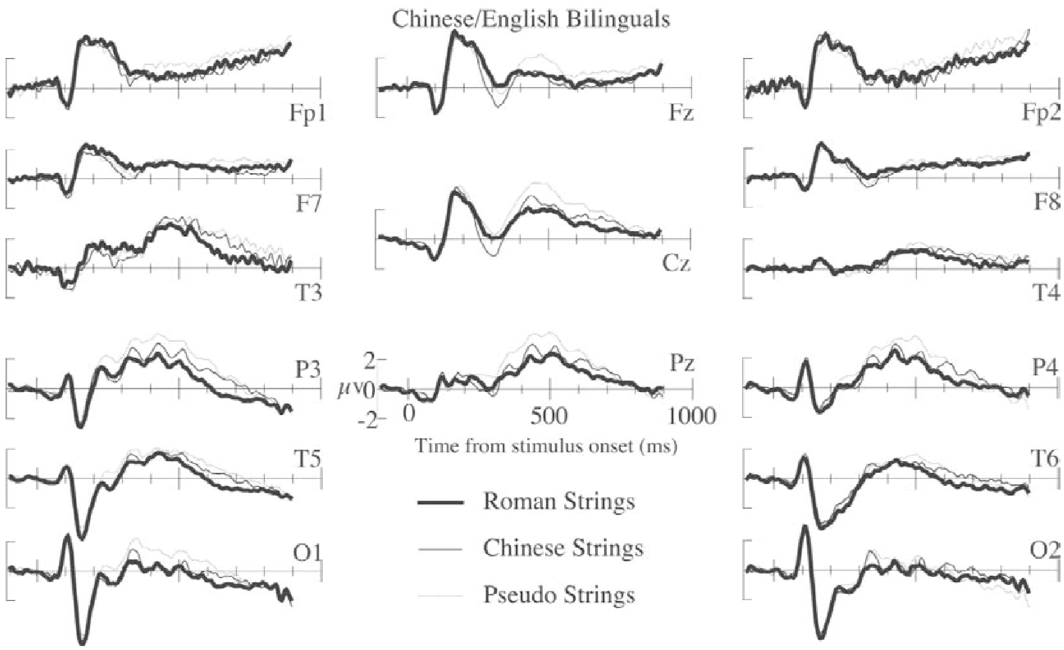

Chinese/English Bilinguals
Fp1
Fz
Fp2
F7
F8
T3
Cz
T4
P3
2
μv 0
-2
0
500
1000
Pz
P4
Time from stimulus onset (ms)
T5
T6
O1
O2
Roman Strings
Chinese Strings
Pseudo Strings

Figure 5

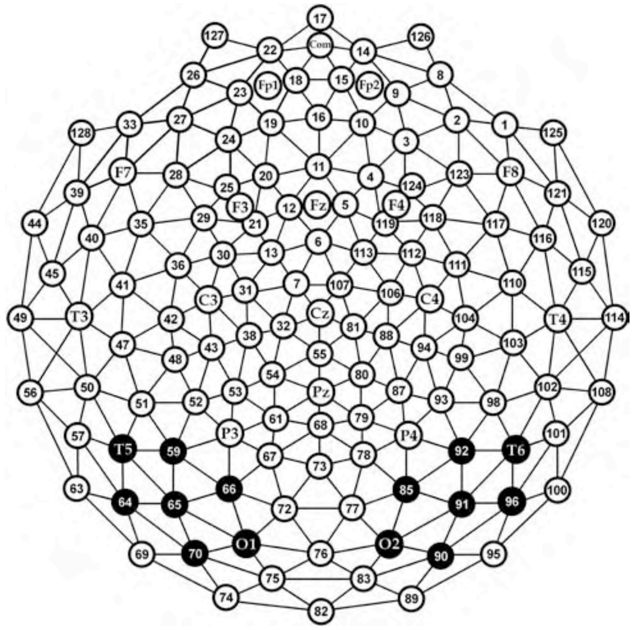

17
127
22
Com
14
126
26
23
Fp1
18
15
Fp2
9
8
128
33
27
24
19
16
10
3
2
1
125
F7
28
25
20
11
4
124
123
F8
39
F3
12
Fz
5
F4
121
44
35
29
21
119
118
117
116
120
40
30
13
6
113
112
111
45
36
31
7
107
106
C4
110
115
41
C3
49
T3
42
32
Cz
81
104
T4
114
47
38
88
94
103
48
43
55
99
54
80
56
50
51
52
53
Pz
87
93
98
102
108
61
68
79
57
T5
59
P3
P4
92
T6
101
67
73
78
63
64
65
66
72
77
85
91
96
100
69
70
O1
76
O2
90
95
75
83
74
82
89

Figure 6

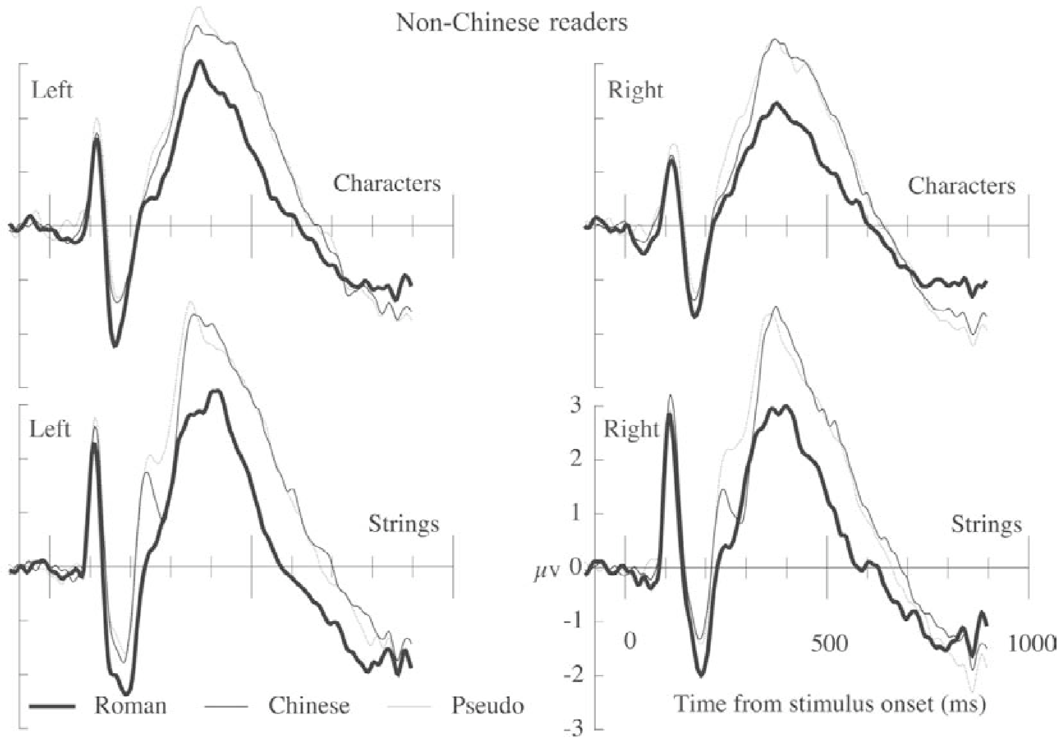

Non-Chinese readers
Left
Characters
Right
Characters
Left
Strings
Right
Strings
3
2
1
μv 0
-1
-2
-3
0
500
1000
Roman
Chinese
Pseudo
Time from stimulus onset (ms)

Figure 7

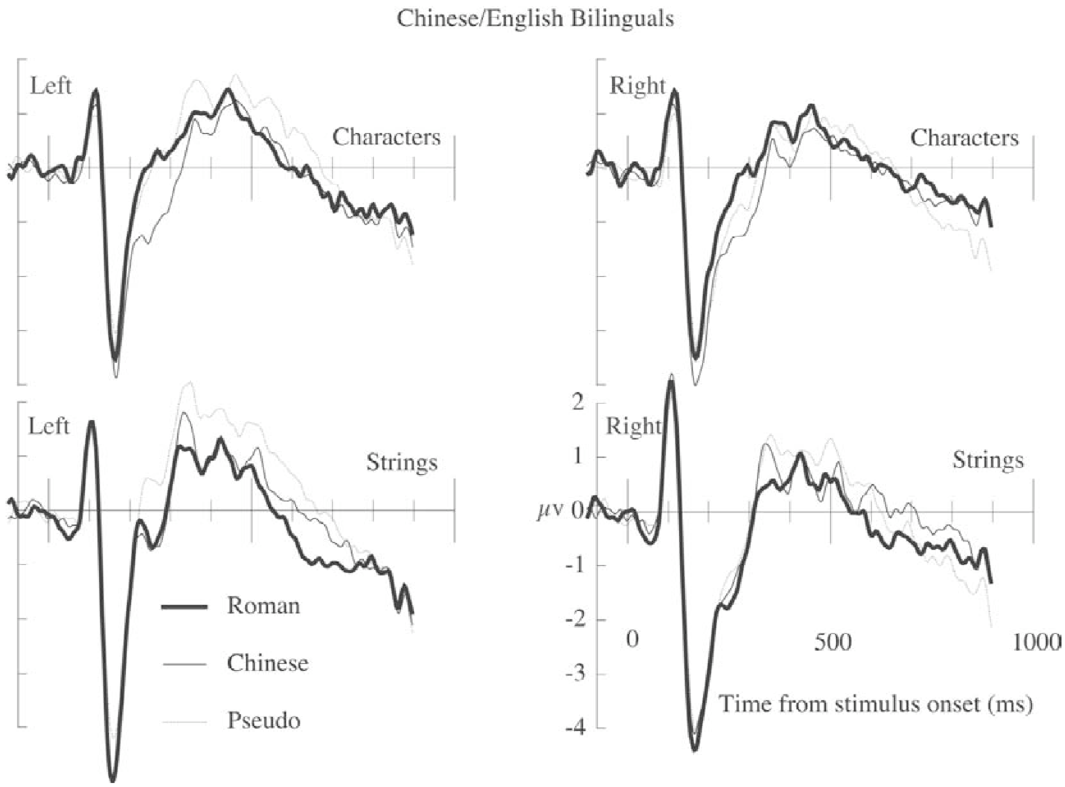

Chinese/English Bilinguals
Left
Characters
Right
Characters
Left
Strings
Right
Strings
Roman
Chinese
Pseudo
2
1
μv 0
-1
-2
-3
-4
0
500
1000
Time from stimulus onset (ms)

Figure 8

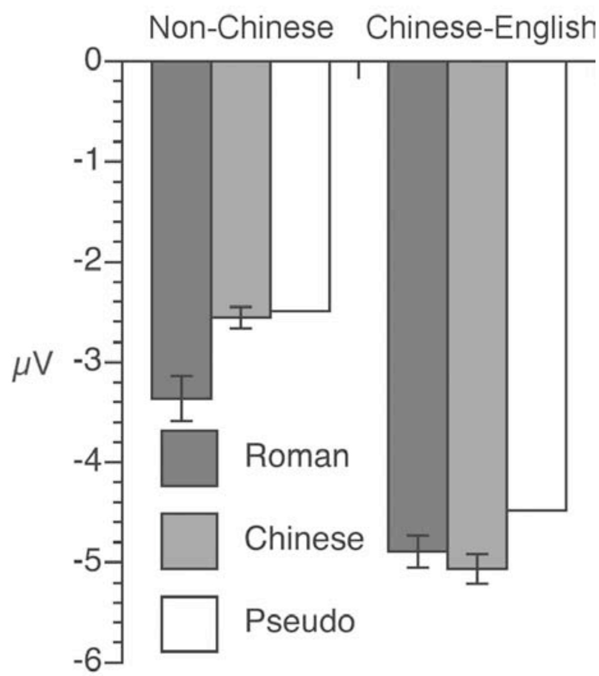

Non-Chinese
Chinese-English
0
-1
-2
-3
-4
-5
-6
μV
Roman
Chinese
Pseudo

Figure 9

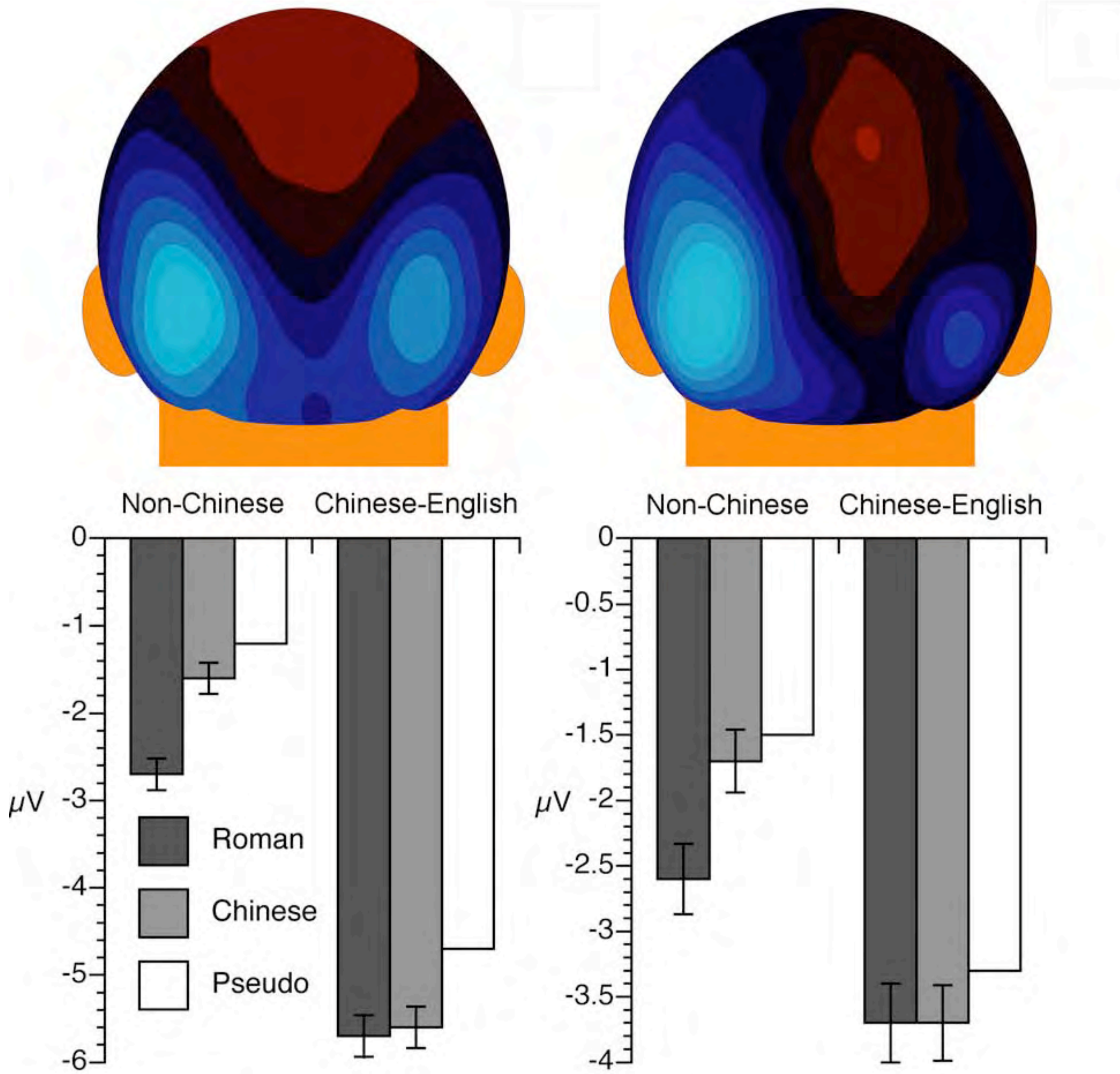

Non-Chinese
Chinese-English
μV
0
-1
-2
-3
-4
-5
-6
Roman
Chinese
Pseudo
Non-Chinese
Chinese-English
μV
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4

Figure 10