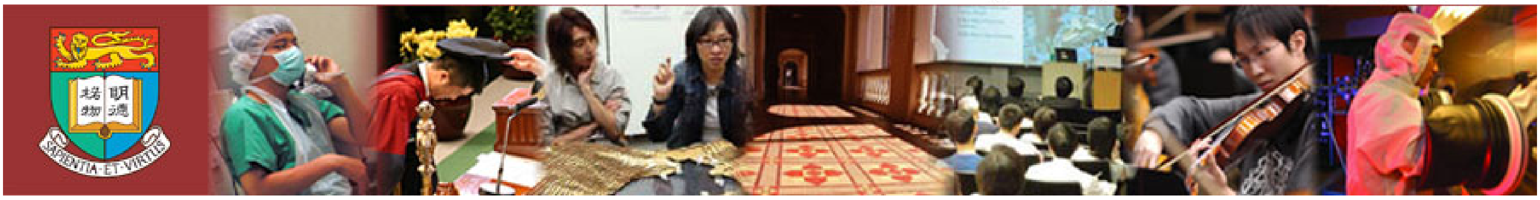

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Logographeme Type And Token Frequency Effects During Chinese Character Recognition:

An Event-Related Potential Study

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Abstract

This study aims to provide evidence supporting the existence of logographeme as a unit of representation during Chinese character recognition. Radicals have long been considered a basic unit in Chinese character recognition. However, in studies of dysgraphic patients, writing errors in characters could not be regarded as radical level errors but were considered logographeme level substitution errors (Law & Leung, 2000; Han, Zhang, Shu & Bi, 2007). To assess whether logographeme also affect the recognition process as found in writing studies, logographeme type frequency (high versus low) and logographeme token frequency (high versus low) were investigated using an event-related potential (ERP) lexical decision task. An interaction between logographeme type and token frequency was found at the occipital N170 component with greater negativity in high type-low token frequency and low type-high token frequency logographemes. Low logographeme type frequency also showed greater negativity at the N400 component. No logographeme effects or interactions were found in the P100 and P200 components. This study provides evidence supporting the existence of logographeme as a unit in Chinese character recognition and that logographemes are activated during orthographic processing stage and perhaps during lexical-semantic retrieval.

Keywords: Chinese character recognition, logographeme, type frequency, token frequency, ERP study, P100, N170, P200, N400

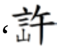
Introduction

Chinese is considered as a logographic or morphosyllabic script, which is different from other alphabetic language systems, such as English. It is suggested that over 80% of Chinese characters are phonetic compounds, which consist of a phonetic and a semantic radical (Zhou, 1992). Different properties of this sublexical unit, including its neighborhood size (Hsu, Tsai, Lee & Tzeng, 2009; Su & Weekes, 2007), consistency (Lee, Tsai, Chan, Hsu, Hung & Tzeng, 2007) and position (Su, Mak, Cheung & Law, 2012) have been shown to have an impact on Chinese character recognition at the neural level. Furthermore, using event-related potentials (ERP), Lee et al. (2007) revealed that character consistency of phonetic radicals had an impact on Chinese character naming at the N170, P200 and N400 components, while Hsu et al. (2009) showed that the orthographic combinability of phonetic radicals demonstrated effects at the N170, P200 and N400 components in homophone detection task. Given these findings, it has been suggested that the way Chinese characters are processed and recognized is likely different from that of other alphabetic languages due to great differences of the representational units in the orthographic form (Perfetti, Liu & Tan, 2005; Taft & Zhu, 1997).

Currently there are two influential Chinese character recognition models, the lexical constituency model (Perfetti et al., 2005; Perfetti & Tan, 1998) and the multilevel activation model (Taft & Zhu, 1997). The lexical constituency model suggests that a word representation consists of three constituent units, which are phonology, orthography and semantics, with the basic graphic unit as radical (Perfetti et al., 2005). In order to for a character to be recognized, Perfetti et al. (2005) argued that there is a threshold of activation for each constituent that has to be reached. Furthermore, graphic information has been proved to be processed before phonological and semantic information in a primed naming task while phonological and semantic information could be processed simultaneously (at the N400 component) or with a time lag in which phonological information starts processing earlier than semantic processing (Perfetti et al., 2005). On the other hand, the multilevel activation model suggested by Taft and

Zhu (1997) claimed that characters are processed from feature level (stroke) to position sensitive radical level and then the whole character level. Via the lemma level, the semantic representation is then activated followed by activation of phonological representation (Taft, 2006). Although the two models differ slightly in the order of which semantic and phonological processing occur, both models suggest that radicals serve as the basic unit that is activated prior whole character activation during orthographic processing of Chinese characters.

However, Yang, McCandliss, Shu, & Zevin (2009) have argued that the specific level of representation of a radical unit is often unclear, for example, ‘白’ [white; /pak$_6$/], can be a (1) single character, (2) a phonetic radical (e.g. ‘伯’ [uncle; /pak$_3$/]), (3) a semantic radical (e.g. ‘魄’ [soul; /p^{h}ak$_3$/), (4) in simple characters or other contexts (e.g. ‘帛’ [silk; /pak$_6$/]) or even (5) a part of another phonetic radicals, which occur in other characters (e.g. the phonetic radical ‘皇’ [king; /wɔŋ$_6$/] in ‘煌’ [bright; /wɔŋ$_6$/]). (IPA system is used for phonetic notation.) This posts a challenge to the current models of character recognition since these radicals are at times not related to the pronunciation or meaning of the characters and they have great variation in positions within characters (Yang et al., 2009). Some evidence has suggested logographeme could be the basic unit of processing based on written errors in case studies of Chinese dysgraphic patients. According to Law and Leung (2000), logographeme is defined as (1) a combination of stroke patterns that are productive and spatially separated and (2) they cannot be further broken down into small logographemes. For example, the logographeme ‘木’ appears in characters ‘休’, ‘村’, ‘紮’, ‘杰’, ‘保’and ‘森’. Unlike radicals, in which a compound character usually consists of two radicals, two or more logographemes can appear within a compound character, and therefore, a radical can often be decomposed into two or more logographemes. For example, in compound character ‘淋’, the phonetic radical ‘林’ can be further decomposed into two ‘木’ logographemes. Amongst all radicals, around 64% of them could be further divided into multiple logographemes while the remaining radicals consist of a single logographeme (Han & Bi, 2009).

The evidence supporting logographeme as basic unit mainly comes from written errors produced by dysgraphic patients. Law and Leung (2000) described a dysgraphic patient SFT, who produced logographeme substitution error, in which he wrote ‘許’ as ‘’. It was not regarded as a radical substitution error since the whole (semantic) radical was not replaced with another radical, but rather, the logographeme ‘口’ in the semantic radical ‘言’ was replaced by another logographeme ‘山’ (Law & Leung, 2000). Han, Zhang, Shu and Bi (2007) later reported another dysgraphic patient WLZ, who produced mainly logographeme errors in a delayed copying task. For example, he substituted the logographeme ‘刂’ with ‘攵’ resulting in a non-character ‘’ instead of the target character ‘箭’. Among all 557 erroneously written characters written by WLZ, 398 of them were logographeme errors that did not correspond to any radical while only 147 of them consisted of errors that could be regarded as logographeme errors or radical errors (Han et al., 2007). Given that logographeme errors were regarded as the most common type of error made by WLZ, and therefore, Han et al. suggested that logographemes exist as a basic functional unit in the orthographic output buffer. Moreover, logographeme as representational unit would have explained the high proportion of logographeme substitution errors (80%) among other error types, in which logographeme was replaced by another logographeme with similar visual properties (Han et al., 2007), such as the writing errors made by SFT and WLZ mentioned above. Based on these studies, it has been suggested that the logographeme representational level could potentially exist between the stroke level and radical level of current model (Law & Leung, 2000).

However, although Law and Leung (2000) and Han et al. (2007) provided evidence supporting logographeme as basic unit in the orthographic output unit for writing, there are currently no studies that directly support the notion that logographemes are used as the basic representation for character recognition. In other words, there is a lack of evidence indicating that existence of logographemes as functional unit in orthographic input unit. Considering the Cognitive Neuropsychological framework for explaining both reading and writing in Chinese suggested by Weekes, Yin, Su and Chen (2006), mapping between semantic information, phonological and orthographic representations are all bidirectional in both the lexical semantic pathway and the non-semantic pathway. Thus, unit in the orthographic representations should arguably be the same for reading (input unit) and writing (output unit). To address current discrepancy in functional levels of representation (radical or logographeme) between orthographic input and output unit, our current research aims at addressing whether logographemes are a basic unit for character recognition. Given that WLZ tended to produce more errors in low token frequency logographemes than high token frequency ones (Han et al., 2007) and that the sublexical radical units demonstrated a type frequency effect previously in behavioral (Taft & Zhu, 1997) and in ERP studies (Hsu et al., 2009; Su & Weekes, 2007), we chose to focus on identifying logographeme frequency effects. Two measures of logographeme frequency were examined: logographeme type and logographeme token frequency. Logographeme type frequency refers to the number of characters that contain a certain logographeme (also referred to family or neighborhood size). For example, the logographeme ‘甘’ can occur in ten different characters, such as ‘酣’ and ‘甜’ and its type frequency is 10 characters. While logographeme token frequency is defined as the number of exposures a logographeme occurs as part of a character. Thus, the same logographeme in the previous example has a token frequency value of 75.8 occurrences per million. Two measures of frequency effects were selected since previous studies investigating radical frequency effects suggested that token frequency is commonly covaried with type frequency (radicals with high type frequency tend to have high token frequency) and their independent effects should be examined specifically (Taft & Zhu, 1997). Furthermore, in a previous study done by Conrad, Carreiras and Jacobs (2008), there was dissociation in type and token frequency effects of syllables in lexical decision task, in which token frequency demonstrated an inhibitory effect while type frequency led to facilitation in lexical decision. Given such a dissociation between type and token syllable frequency, Conrad et al. (2008) claimed that type and token syllable frequency might be related to different processing stages during word recognition. While type frequency effect may enhance the initial orthographic processing in prelexical stage, token frequency may play a role at the lexical processing stage resulting in inhabitation due to frequency of syllable neighbors (Conrad et al., 2008). Based on these observations, it may also be likely that logographemes may be sensitive to different types of frequency features.

Along with behavioral data, ERP data will also be collected since it has very fine temporal resolution (Luck, 2005) and has been shown to be able to capture the very fine temporal differences in cognitive processes involved in radical processing during character recognition and naming (e.g. Hsu et al., 2009; Perfetti, Liu & Tan, 2005). Logographeme effects have not been previously reported using ERP measures, however, since sub-lexical units are believed to be processes at the early stage of character recognition as hypothesized by Su et al. (2012), early ERP components, including P100, N170 and P200 components will be the foci. Furthermore, logographemes are hypothesized to be activated at the sublexical level before whole word representation is activated in the lexical constituency and multilevel activation models of Chinese word recognition (Perfetti et al., 2005; Perfetti & Tan, 1998; Taft & Zhu, 1997), and therefore, may show effects before lexical level activation during pre-lexical access. Note that although ERP studies on logographeme processing are lacking, our ERP prediction have been extrapolated from ERP studies on radical processing since both radical and logographeme representations can overlap, like in ‘酣’, ‘甘’ is a logographeme and phonetic radical at the same time and are both possible sub-lexical units in Chinese character recognition process.

The P100 component (about 100ms post-stimuli) at electrodes in the occipital region (Key, Dove & Maguire, 2005) is sensitive to visual features, for example, stimuli complexity and spatial property (Dien, 2009; Hauk & Pulvermüller, 2004; Su et al., 2012). In particular, the P100 component was shown to be sensitive to orthographic neighborhood size (analogous to type frequency of sublexical units) of letter strings (Hauk, Pulvermüllerm, Ford, Marslen-Wilson & Davis, 2009). It is suggested that the P100 component showed greater positivity in stimuli with larger orthographic neighborhoods due to the partial activation of memory traces of their neighbors during processing (Hauk et al., 2009). If logographemes serve as a functional sublexical unit, which is then loosely comparable to letter strings in alphabetic scripts, logographemes with high type frequency are predicted to show larger positivity in the P100 component. Moreover, if logographeme type or token frequency effect occurs as early as at P100 component, this would suggest that logographeme processing is likely to be functioning at a purely visual analysis level.

The word-N170 component (156-189ms) at electrodes in the occipital region (Key et al., 2007) is associated as indexing orthographic detection by Hsu et al., (2009) and represents sublexical processing in general (Dien, 2009). The N170 component has generally shown greater negativity for low frequency words (Hauk & Pulvermüller, 2004; Sereno, Rayner & Posner, 1998). More negative N170 component was also observed when radicals occur in their non-preferred (less frequent) position in a primed-lexical decision task (Su et al., 2012). Focusing on radical type frequency, radicals with larger neighborhood size have shown a great N170 activation during a homophone judgment task (Hsu et al., 2009). Given its sensitivity towards sublexical processing and radical type frequency effects, it is hypothesized that N170 may elicit a greater negativity for logographemes with low token frequency and high type frequency. If logographeme frequency effects at N170 component are found, this may imply that logographemes are processed at the orthographic sublexical level during time course of word recognition.

The frontal P200 component (170-270ms) at electrodes in the frontal region (Hsu et al., 2009) is often reported together with the occipital N170 component in Chinese, and is suggested to reflect orthographic and phonological processing as well as mapping between orthography and phonology (Hsu et al., 2009; Liu et al., 2003). In Hsu et al., (2009), radicals with larger neighborhood size showed less positive P200 due to facilitation by previous greater orthographic activation at the N170 component. Based on this finding, it is proposed that logographemes with high type frequency is likely to show less positivity as radicals with larger neighborhood sizes. Observation of logographeme frequency effects at the P200 component would imply that logographemes are activated at the level of orthographic and phonological processing or the mappings between them.

Lastly, the N400 component (300-450ms) at electrodes in the central region (Hsu et al., 2009; Su et al., 2012) will be investigated in this study. The N400 component is an ERP component that reflects lexical semantic access (Holcomb, Grainger & O'Rourke, 2002; Hsu et al., 2009; Liu et al., 2003; Su et al., 2012). Sublexical units with higher type frequency were associated with a more negative N400 component in previous studies due to more lexical competition from a larger neighborhood in studies using lexical decision and naming tasks (Holcomb et al., 2002; Hsu et al., 2009; Su et al., 2012). Thus, it is predicted that logographemes with high type frequency will show a more negative N400 due to lexical competition. While logographemes with high token frequency is likely to evoke a smaller N400 since previous study showed that N400 tends to decrease in amplitude with increasing word frequency, reflecting greater ease as access to lexical semantic representations (Hauk & Pulvermüller, 2004).

The findings of this study have strong implications to current Chinese word recognition models (Perfetti et al., 2005; Perfetti & Tan, 1998; Taft & Zhu, 1997) since logographemes do not currently exist as a functional unit in any models, as well as address the necessity for separate input and output lexicons used between reading and writing. Combining with previous studies showing that logographeme serve as a basic unit in the orthographic output unit, evidence supporting that it also serves as a functional unit in the orthographic input unit will be groundbreaking and provides sufficient evidence information for modifying current character recognition models (Perfetti et al., 2005; Perfetti & Tan, 1998; Taft & Zhu, 1997).

Method

Participants

A total of 29 participants native Cantonese speakers within the age range 19-27 years old were recruited. Four participants were excluded in behavioral analysis due to response bias in lexical decision (with difference in accuracy of determining real and pseudo characters greater than 20%). After artifact rejection, another three participants were excluded in ERP data analysis due to extremely small number of valid trials in their data (less than 15 trials in any one condition). Hence, the behavioral data analysis was conducted with 25 participants. Their mean age was 22.6 years old (*SD* = 1.8). Fourteen participants were male and 11 participants were female. All participants were right-handed with an average Edinburgh Handedness Questionnaire score of +76.1 (*SD* = 19.5; Oldfield, 1981). All participants had completed secondary education in local mainstream schools and were undergraduates or graduates from the University of Hong Kong or other universities in Hong Kong. All participants had normal or corrected vision and did not have previous history of developmental language difficulty or neurological disorders.

Design and Materials

A logographemes database (Lui, Leung, Law & Fung, 2010) with a total of 249 logographemes and 3764 characters and the Hong Kong Corpus of Chinese Newspaper containing data of character frequency (Leung & Lau, 2010) were used to select the character stimuli. First, target logographemes were selected based on their type frequency and token frequency. Type frequency refers to the number of characters that contain a certain logographeme. Using the logographeme database, the range of low and high type frequency was determined by selecting logographemes within the lower 35% or upper 35% of all 249 logographemes, see Table 1 for the frequency ranges. Of the logographemes in the upper or lower 30% of the type frequency range, logographeme were then selected to be of either high or low token frequency as defined by the number of exposure of characters that contains the specified logographeme per million.

Table 1. Range of type and token frequencies for logographeme selection

Parameters	Low Range	High Range
Type Frequency (characters)	3 – 15	34 – 155
Token Frequency (number of occurrence per million)	49 – 157	206 – 361

This lead to the selection of 29 high type-high token logographemes (e.g. ), 22 high type-low token logographemes (e.g. ), 17 low type-high token logographemes (e.g. ) and 28 low type-low token logographemes (e.g. ) fulfilling the criteria in Table 1. Then 40 characters containing only one of the target logographemes were chosen as stimuli for each condition, while the other (non-target) logographemes within the character did not overlap with other target logographemes from other conditions. Note that as the number of target logographemes were fewer than those required to obtain high signal-to-noise ratio for ERP analysis, target logographemes could appear more than once in a different character within the same experimental conditions. Thus, a total of 160 real characters were selected based on the type frequency (low vs. high) and token frequency (low vs. high) of logographeme, see Appendix 3 for list of stimuli. Another 160 pseudo characters were then made by combining logographemes in real characters randomly to act as fillers in the lexical decision task.

Figure 1. Example of real and pseudo characters

Number of strokes, number of logographemes, character frequency and radical combinability were controlled among different condition to avoid confounds, see Table 2 for detailed statistics. Between-group 2 x 2 two-way ANOVA analysis showed no significant differences among the above parameters.

Table 2. Statistical information of parameters across type and token frequency conditions

	Low Type		High Type			
	Low Token	High Token	Low Token	High Token		
Parameters	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*F*	*p*
Type	8.85 (2.57)	10.88 (3.47)	68.15 (29.11)	78.95 (33.20)	-	-
Token	94.43 (27.46)	282.71 (47.72)	116.51 (34.69)	226.21 (35.82)	-	-
NOS	11.80 (2.50)	11.43 (3.72)	11.03 (3.00)	10.47 (2.86)	$F(3,156) = 1.38$	.25
CF	71.67 (77.87)	86.24 (110.89)	82.72 (116.82)	48.29 (52.27)	$F(3,156) = 1.89$	.13
NOL	3.70 (0.94)	4.07 (0.97)	3.62 (0.81)	3.73 (0.96)	$F(3,156) = 1.35$	.26
RC	2.48 (2.08)	3.15 (2.92)	2.88 (2.41)	2.95 (2.56)	$F(3,156) = 0.51$	.68

Note. Type = type frequency; Token = token frequency (per million); NOS = number of strokes; CF = character frequency (per million); NOL = number of logographemes; RC = radical combinability.

Procedure

A lexical decision task was applied in this experiment, in which participants were instructed to click one button on the mouse with thumb of one hand in response to a real character and another button with thumb of the other hand in response to a pseudo character. Figure 2 illustrates the trial duration and sequent of the task. Yellow characters were presented on a black background on a computer screen with a distance of approximately 80cm from the participant. The experiment, participant's reaction time and accuracy were presented and was collected using E-Prime (2.0) respectively. Ten practice trials were given before the experiment started. The whole experiment consisted of four blocks in randomized order with 80 trials in each block. Each block contained 40 real characters (ten from each low type-low token, low type-high token, high type-low token, high type-high token condition) and 40 pseudo characters all randomly presented. Counterbalancing of left and right hand across participants was done to avoid handedness-related lateralization effects. Electroencephalographic

(EEG/ERP) data was collected simultaneously with the behavioral data that included accuracy and reaction time of the participant's response.

Figure 2. Trial sequence of the paradigm

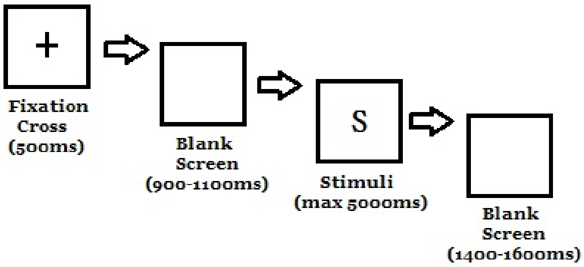


Figure 2. Each trial began with a fixation cross followed by a blank screen with an average duration of 1000ms before a character stimulus was present for a maximum of 5000ms and followed by a blank screen for an average of 1500ms. The duration of blank screen before and after stimuli was randomly varied between 900-1100ms and 1400-1600ms respectively to avoid anticipation effects.

EEG Data Recording

The electroencephalogram (EEG) was measured in an electrically, magnetically and acoustically shielded booth at the EEG lab at the Laboratory of Communication Science in the University of Hong Kong. Data was collected with 64 Ag/AgCl electrodes mounted on a cap (QuickCap, Neuromedical Supplies, Sterling, USA) according to the extended 10-20 system with a common vertex reference located between electrode CPz and Cz. A ground electrode was located anterior to electrode Fz near the forehead. Vertical eye movement was recorded by two electrodes located on the supraorbital and infraorbital ridges of the left eye while horizontal eye movement was recorded by two electrodes placed at the outer canthi of both eyes. The EEG data was recorded at a sampling rate of 1000Hz and amplified by SynAmps (NeuroScan Labs, Sterling, USA).

EEG/ERP Data Processing

For the offline analysis of EEG data, first bad channels were removed and unwanted affected by extensive movement artifacts data was marked. The AF3 electrode was removed in one of the participants. Then a band-pass filter of 0.05Hz to 30Hz (12dB, zero phase shift mode) was applied and ocular artifact reduction was implemented to reduce eye blink artifacts.

Then each trial was epoched with 200ms before stimuli onset window and 1000ms after stimuli onset. Baseline correction was done with the pre-stimuli interval (-200ms to 0ms) followed by artifact rejection, in which trials with voltage variation greater than ±70µV and incorrect trials were rejected, and re-referenced to the whole head average (GFP). A total of 18% of trials were rejected in the artifact rejection or due to incorrect respond. The ERPs of all correct trials at all electrodes of every participant were averaged according to different stimuli conditions for further statistical analysis.

Data Analysis

Incorrect trials and response ± 2.5SD of the mean (pseudo characters: 1.7%; real characters: 0.62%) were excluded for the reaction time analysis. Reaction time and accuracy data were extracted and a two-tailed by-participant repeated measures *t*-test and by-items independent measures *t*-tests comparing real and pseudo characters was used in the accuracy and reaction time analysis. In the subsequent analyses, the pseudo characters filler trials were removed and a 2 x 2 two-way repeated measures ANOVA with independent variables as type frequency (high vs. low) and token frequency (high vs. low) for the by-participant analysis. Another 2 x 2 two-way independent ANOVA was conducted for items analysis. Post hoc tests with Bonferroni corrections were done to compare data of each condition. Incorrect trials and response ±2.5SD of the mean (i.e. too fast or too slow responses) were excluded for the reaction time analysis.

To extract the ERP components P100, N170, P200 and N400, their amplitude within their particular time windows was selected based on their peaks shown in the Mean Global Field Power (MGFP) grand average waveforms (P100: 70-130ms; N170: 100-200ms; P200: 170-270ms; N400: 300-450ms). For ERP components P100 and N170, since they were early visual ERP components and were believed to be originated from the visual cortex, electrodes at the occipital area (PO5, PO6, PO7, PO8) were selected for analysis (Hsu et al., 2009). P200 component was detected in the frontal region, and electrodes at the frontal area (FC1, FC2, FC3, FC4) were selected for analysis (Hsu et al., 2009). P100, N170 and P200 components were analyzed separately by a 4-way repeated measure ANOVA with hemisphere (left vs. right), electrodes (inner vs. outer), type frequency (high vs. low) and token frequency (high vs. low) as independent variables. For the semantically related ERP component N400, electrodes along the midline were selected (Fz, Cz, Pz)(Hsu et al., 2009). It was analyzed by a 3-way repeated measure ANOVA with electrodes (Fz vs. Cz vs. Pz), type frequency (high vs. low) and token frequency (high vs. low) as independent variables.

Results

Behavioral Findings

In the behavioral data analysis, there was a main effect of lexicality on reaction time, $t_1(24)= 3.91$, $p < .01$, $t_2(318)= -9.17$, $p < .01$, in which participants tended to respond faster towards real characters than pseudo characters, see Table 3. On the other hand, the accuracy analysis only showed a main effect of lexicality in the item analysis but not in the participant analysis, $t_1(24)= -.67$, $p = .51$, $t_2(318)= 4.76$, $p < .01$, in which real characters were easier to identify than pseudo characters.

Table 3. Mean and standard deviation of behavioral data in lexicality

	Real characters	Pseudo characters
	M (SD)	*M (SD)*
Accuracy (%)	94.6 (3.18)	93.6 (5.82)
Reaction time (ms)	664 (101)	736 (132)

Considering the effect of type and token frequency of logographemes, no main effects were found in the accuracy and reaction time analysis (all F’s < 1.84, p’s > .19, $\eta_p^2 = .07$). An interaction between type and token frequency however was found only to be significant in the by-participant analysis, but not in the by-item analysis, $F_1(1, 24) = 7.41$, $p < .05$, $\eta_p^2 = .24$, $F_2(3, 156) = .56$, $p = .46$, $\eta_p^2 < .01$. Post-hoc pairwise comparisons indicated that high type-low token frequency logographemes tended to have lower accuracy than high type-high token frequency ($M_{difference} = 2.2\%$, $SE = 0.9\%$; $p < .05$) and low type-low token frequency ($M_{difference} = 2.2\%$, $SE = 0.8\%$, $p < .05$).

Table 4. Statistics of latency and accuracy across the different type and token frequency conditions

	High Type Frequency		Low Type Frequency	
	High Token Frequency	Low Token Frequency	High Token Frequency	Low Token Frequency
Parameters	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Reaction Time (ms)	668 (102)	666 (106)	652 (106)	669 (107)
Accuracy (%)	95.4 (3.4)	93.2 (4.9)	94.5 (3.4)	95.4 (3.8)

Electrophysiological Findings

Based on the MGFP, the first positive deflection had a maximal peak in the occipital regions at 95ms from stimuli onset followed by a negative deflection at 155ms. A small positive deflection in the frontal electrodes with a peak at 250ms and a central negativity peaking at 330ms were observed. The grand average waveforms and topographic plots at the P100, N170, P200 and N400 components are in Figure 4 and Appendix 2 respectively.

Figure 4. Grand average waveforms for the effects of logographeme type and token frequency at P100 and N170 (electrodes PO7, PO8) and N400 (electrodes FZ) components (waveforms of all target electrodes are included in Appendix 1)

P100 component (75-125ms)

A main hemispheric effect was found, $F(1,21) = 5.53$, $p < .05$, $\eta_p^2 = .21$, in which the right hemisphere elicited greater positivity than the left hemisphere in reading characters ($M_{difference}$ = 1.01μV, $SE = 0.43$), see Figure 5. No main effect on logographeme type frequency, token frequency or other interactions were found (all *F*'s < 1.82, *p*'s > .19).

Figure 5. Mean amplitudes of main hemispheric effect at the P100 component

Occipital N170 component (125-175ms)

No main effect of logographeme type frequency and logographeme token frequency (All *F*'s(1,21) < 0.05, *p*'s > .83) were found. However, there was a significant interaction of type and token frequency of logographeme, $F(1,21) = 6.49$, $p < .05$, $\eta_p^2 = .24$, suggesting that logographeme token frequency was affected by the logographeme type frequency, see Figure 6 (left). In the post-hoc pairwise comparisons, logographemes with low type-high token frequency and high type-low token frequency conditions tended to have greater negativity compared to ones with low type-low token frequency and high type-high token frequency. In the post hoc pairwise comparisons, logographemes with high token frequency elicited significantly greater negativity than those with low token frequency when they have small neighborhood size ($M_{difference}$ = 0.62μV, $SE = 0.26$, $p < .05$) and was close to significant when they have large neighborhood size ($M_{difference}$ = 0.68μV, $SE = 0.37$, $p = .085$). On the other hand, for characters with high token frequency condition, logographemes with low type frequency elicited a significantly greater negativity than those with high type frequency ($M_{difference}$ = 0.69μV, $SE = 0.28$, $p < .05$). A significant interaction between hemisphere, type frequency and token frequency was also found ($F(1,21) = 4.84$, $p < .05$, $\eta_p^2 = .19$), indicating that the degree of the interaction between type and token frequency was significantly different between the left and right hemisphere, see Figure 6 (middle and right). Follow-up comparisons showed that in the right hemisphere, significant type frequency effects we found in both low token ($M_{difference} = 1.01\mu V$, $SE = 0.46$, $p < .05$) and high token conditions ($M_{difference} = 1.04\mu V$, $SE = 0.36$, $p < .01$) that were similar in nature to significant two way interaction reported above. Likewise, significant token frequency effects were found in characters in high logographeme type frequency condition ($M_{difference} = 1.29\mu V$, $SE = 0.48$, $p < .05$). However, no significant effects were found in the left hemisphere (all p's > .18) suggesting that the type by token frequency interaction is constrained to the right hemisphere.

Figure 6. Mean amplitudes of interactions at the N170 component

Figure 6. Left: amplitudes of the two-way interaction; middle: amplitudes of interaction in the left hemisphere; right: amplitudes of the interaction in the right hemisphere

P200 component (210-270ms)

No main effect on logographeme type frequency, logographeme token frequency or other interactions were found (all F's < 1.50, p's > .23).

N400 component (250-400ms)

A main effect of logographeme type frequency was found, $F(1,21) = 5.56$, $p < .05$, $\eta_p^2 = .21$, showing that logographemes of low type frequency condition evoked a more negative N400 component than those of high type frequency condition ($M_{difference} = 0.22\mu V$, $SE = 0.09$), see Figure 7. On the other hand, there was no significant logographeme token frequency effect and no other main effects or interactions were significant (all F's < 0.43, p's > .582).

Figure 7. Mean amplitudes of main type frequency effect at the N400 component

To summarize, the behavioral findings suggest weak logographeme effects, as significant logographeme effects were only apparent in the by-participant accuracy analysis. The ERP findings, on the other hand, showed that there is an interaction between logographeme type and token frequency at the occipital N170 component and such interaction was more significant in the right hemisphere. In the later N400 component, there was also a main effect of logographeme type frequency, in which logographemes with lower type frequency elicited more negativity in the N400 component. A general hemispheric effect was also found in the occipital P100 component, in which the right hemisphere showed greater positivity than the left during character reading.

Discussion

The aims of this study were to provide evidence of whether logographemes was an existing unit during Chinese character recognition, and if indeed existed, determine how logographemes are processed and inform current models of Chinese character recognition (e.g. interactive constituency model [Perfetti & Tan, 1998] and multilevel interactive activation framework [Taft & Zhu, 1997]). Unlike previous studies on logographemes, this study did not focus on investigating logographemes as a unit in writing, but was interested in how they are processed in reading. Although the behavioral results showed little logographeme effects, in which only an interaction was found between logographeme type frequency and token frequency in accuracy, it nonetheless suggests that logographemes play a role in making the accurate selection of the character form in the lexicon. No effect or interaction was found in reaction time implying that the overall type and token frequency effects of logographemes on processing time may be less relevant. On the other hand, using more sensitive electrophysiological measures to capture the time course of logographeme processing, the ERP findings revealed an early logographeme effect at the occipital N170 and later N400 components. Neural sensitivity to type and token frequency of logographemes at N170 component further supports logographeme as an orthographic unit affecting visual word form processing and may impact on later semantic access or retrieval during the character recognition process. The following discussion will focus on the elucidating the time course of logographeme processing based on the main effects and interaction of type and token frequency reflected by the ERP and accuracy findings, potential confounds within the study, and attempts to integrate findings of logographeme processing into current models of character processing.

In the behavioral findings, the significant interaction effect was mainly due to when a character with a logographeme of high type-low token frequency (many neighbors but few exposures), participants were poorer in accuracy to identify the character as real than compared to the other logographeme conditions, the accuracies were higher, which results in such an interaction. Given that logographemes that have high type frequency have more possible combinations with other logographemes to form a character, it is argued that logographemes with larger neighborhood size are harder select the word form accurately for lexicality judgment. Considering the interactive constituency model (Perfetti & Tan, 1998), it is suggested that logographemes representation would be at orthographic level activated before whole character and radical representation (Law & Leung, 2000). Within the interactive constituency model, when a certain character is present, the logographemes representation within the character will be activated and send information to the subsequent levels of orthographic representations (either directly to the whole character level or radical level since currently, it remains uncertain the routes of orthographic processing involving logographeme level). Moving up to the next level, the radicals / characters containing that logographeme will also be activated, which create competition. Only the radicals and characters containing all activated logographemes will be able to reach the threshold for recognition. Therefore, with a larger neighborhood size, more radicals / characters will be activated and create greater competition amongst candidate characters. Hence, the possibility of failure in lateral inhibition during the selection process will be higher resulting in error in lexicality judgment. And while logographemes with low token frequency are less exposed to less, greater activation may be needed to reach the threshold for recognition of its candidate character representations, and thus errors would be more likely to occur when identifying the character. As a result of a double disadvantage, both factors together may give rise to lower accuracy in lexical decision. Similar processing would be expected in the multilevel activation framework (Taft & Zhu, 1997) as well with logographeme level in between feature level and radical / character level.

Considering the ERP findings, the presence of type and token frequency interaction effect at the occipital N170 could indicate that logographemes play a role in early visual word form stages of orthographic processing from as early as 125ms. Low type-high token frequency and high type-low token frequency conditions tended to have greater negativity when compared to low type-low token and high type-high token frequency conditions respectively. Part of such interaction could be explained by the token frequency effect. Such token frequency effect is a result of prolonged experience in reading characters of a familiar writing system and the visual recognizing process is optimized as a result of such long-term exposure, which is also referred as expertise effect with character reading in some studies, for example, in Maurer, Zevin and McCandliss (2008) and Wong, Gauthier, Woroch, Debuse and Curran (2005). It is shown in previous study that token frequency effect on words will elicit a greater N170 component (Maurer et al., 2008; Simon et al., 2007) and letter has also shown to have a token frequency effect in previous study (Wong et al., 2005), and thus, in this study, logographemes as a component of character could possibly be considered to be analogous as the direction of the token frequency effect appears to be in the similar direction since previous studies on writing demonstrated that logographemes in Chinese script are comparable basic unit to letters in the alphabetic script (Han et al., 2007). Such token frequency due to more exposure to that particular logographeme will result in more extensive neural network (Maurer et al., 2008). When the logographeme with high token frequency is recognized, it will create greater neural activation due to stronger neural network. However, its impact on the orthographic-perceptual analysis stage is only constrained characters with a small logographeme neighborhood size, given the significant interaction found between type frequency and token frequency of logographemes at the N170 component. However, when the logographemes have large neighborhood size, less exposure ones will evoke a more negative N170 component. This is in line with studies investigating token frequency of words (Hauk & Pulvermüller, 2004; Sereno et al., 1998). Since more exposure will result in more efficient neural network as suggested above, in this case, logographeme with high token frequency however will require less activation in order to be recognized compared with low token frequency one (Hauk & Pulvermüller, 2004). Thus, the N170 interaction effect suggests that type and token frequency effects have an inter-related impact on character recognition, where when the neighborhood size varies, the amount of exposure of the logographeme influences the process of character recognition differently.

Such interaction was found to be mainly driven by the right hemisphere as reflected by the significant three-way interaction between hemispheres, type frequency and token frequency. Although in previous studies, effects on word-related occipital N170 component are usually left lateralized (Hsu et al., 2009; Simon et al., 2007), our findings could imply that logographemes are processed primarily in the right hemisphere. Since visual spatial and holistic processing has been argued to be more dominant process in the right hemisphere and such processing is more important in logographic script like Chinese than alphabetic language (Kim, Yoon & Park, 2004), the logographeme right lateralization effects would suggest that logographemes may be primarily involved in visual spatial processing of the characters orthographic's form. Noted that the right hemisphere bias contrasts with previous studies of radical processing in Chinese where there has been a tendency to observe left lateralization (Su et al., 2012) or bilateral activation (Hsu et al., 2009). Difference in the topographic loci of logographeme and radical effects further supports that logographemes are distinct and play a different role from radicals in orthographic processing. However, it remains to be seen whether further logographeme processing studies will replicate a right hemisphere bias.

Note that no effect or interaction was found in the occipital P100 component, possibly suggesting that logographemes is not a pure visual unit and its features are not active before 100ms (Dien, 2009). This contrasts with Sar (2014) findings that the number of logographemes in a character demonstrated an early effect, in which characters with fewer logographemes evoked a smaller P100. Differences in results may be due to the properties of logographemes investigated in this study, which are logographeme type and token frequency, as such type frequency may have its impact at the lexical stage and token frequency may affect the prelexical stage as suggested in study on syllable type and token frequency (Conrad et al., 2008). Type and token frequency may not show their effect at such an early stage, whereas logographeme number effects were showed at early P100 component (Sar, 2014). Apart from P100 component, no significant effects or interactions were found at the subsequent frontal P200 component. As P200 component is suggested to reflect the mapping between orthography and phonology in Chinese, it can be argued that logographemes are not relevant to the access or retrieval of the phonological form of the character (Liu et al., 2003) or phonetic radical (Hsu et al., 2009). As suggested by Han and Bi (2009), only about 49% of these logographeme components can be pronounced and even if the character contains pronounceable logographemes, the pronunciation of the character is rarely related to the phonological forms of its logographemes. Therefore, the non-significant results at the P200 component supports the notion that logographemes serve as a basic orthographic unit, and plays little role during access and/or selection of the character’s phonological form during phonological processing of Chinese characters.

Apart from effects in N170 component, type frequency effect was found in N400 component, in which low type frequency showed greater negativity. More negativity at the N400 component represents increased effort for lexical-semantic access or greater lexical semantic or semantic competition (Holcomb, Grainger & O’Rourke, 2002; Hsu et al., 2009). Taken together, our findings imply that logographemes with small neighborhood size are harder to access in the lexical semantic processing stage or exert greater lexical semantic competition with candidate characters that may share similar logographemes. However, the results appear counter-intuitive given that characters with logographemes of a smaller neighborhood would have fewer lexical competitors in the neighborhood. It could be possible that the effects at the N400 component may be somewhat confounded with radical effects that have been previously reported at the N400 component (Hsu et al., 2009; Su et al., 2012; Su & Weekes, 2007). The target logographemes in stimuli of high type frequency condition were more likely to also stand as radicals than those in low type frequency, thus potentially indicating that characters in the high type condition may tend to contain radicals with larger radical neighborhood size. However, radicals with larger neighborhood size have been shown to elicit greater N400 component due to increased semantic competition in previous studies (Hsu et al., 2009; Su et al., 2012). Even with this potential confound, it would have been expected that characters with high type frequency logographemes would elicit a greater N400 component rather than the low type frequency characters, as in the case of this study. As each character only contains one target logographeme in one of the experimental conditions, to look for possible alternative explanations of this unexpected type frequency effect of logographeme, the type and token frequencies of other logographemes within the chosen characters were investigated. Significant difference was found in average type frequency of the non-target logographemes between high and low type frequency conditions, $F(3,156) = 5.98$, $p = .016$, while no significant difference was found in average token frequency of non-target logographemes between high and low token frequency conditions, *F*(3,156) = 2.29, *p* = .132. Among the non-target logographemes, the average type frequency of low type frequency condition was indeed significantly higher than that of high type frequency condition, which could possibly confound in this study. Since other non-target logographemes within the characters in low type frequency condition tend to have larger neighborhood size, more lexical-semantic competition from candidate characters that share the target and non-target logographemes may be cause the greater more negativity at the N400 component. Upon the exclusion of 3 stimuli in each condition (removal of a total of 12 stimuli), the difference between type frequency of non-target logographemes became non-significant, *F*(3,144) = 2.54, *p* = .113. And therefore, it is estimated that 7.5% of the data was affected by this confound.

Such a confound may also affect the interaction between logographeme type and token frequency at the N170 component, in which within the characters of high logographeme token frequency, logographemes with low type frequency showed more negativity and argued to be easier to recognize. Given that the non-target logographemes within the characters actually have a larger neighborhood size, they are likely to facilitate the orthographic recognition process, which in turn shows a more negative N170 component since large neighborhood size was proved to facilitate recognition process in previous studies on letter strings (Wong et al., 2005) and radicals (Hsu et al., 2009). Although the type frequency was affected due to confound of non-target logographemes within the character, nonetheless, the logographeme token frequency remains as providing some support for the existence of logographemes effect at the N170 component as discussed above. Note also that while the logographeme type frequency effect in the interaction with token frequency effect at the N170 component may be affected by the current confound and would require further investigation. Reanalyzing the data of current study by removing the 7.5% affected data would be a possible way to remove such experimental confound and modify the current findings. This was not done due to time constrain. It is important to note however that the contribution from non-target logographemes that lead to this confound in current study is extremely difficult to control for since it is near impossible to ensure that the type and token frequencies of all logographemes within a target character all belong to the same condition while maintaining enough character items to achieve good signal-to-noise radio for the electrophysiological recordings. It is proposed that future studies could investigate the logographeme type and token frequency effect by using pseudo characters rather than existing characters. This would lead to better control of each logographemes within the pseudo character and avoid the confound present in current study.

Lastly, a hemispheric effect was found in the early occipital P100 component, in which right hemisphere demonstrated more activation than the left hemisphere when processing the characters in general. Although most studies report a left lateralization of P100, particularly for words in alphabetic scripts (Hauk et al., 2009; Rossion et al., 2003), some do reported more activation in right hemisphere in Chinese (Hsiao, Shillcock & Lee, 2007). This suggests that Chinese orthography is more logographic in nature (Rossion et al., 2003) and requires finer spatial analysis compared with alphabetic scripts as spatial processing is suggested to be dominant in the right hemisphere (Kim et al., 2004).

Considering current models of Chinese character recognition, both interactive constituency model (Perfetti & Tan, 1998) and multilevel interactive activation framework (Taft & Zhu, 1997) do not include logographemes in one of the components in Chinese character recognition. Based on the findings of this study, it is argued that logographemes play a role in the recognition process, and therefore, these models may have to be revised to accommodate logographemes. In the interactive constituency model, radical was the basic unit in the three constituents, including orthography, phonology and semantic (Perfetti & Tan, 1998). Logographeme could be one of the basic units in the orthography constituents. However, as logographemes do not contribute to phonological processing (as revealed in the P200), they are not likely to be a functional basic unit in the phonological and semantic constituents. It is suggested that logographemes in the multilevel interactive activation framework (Taft & Zhu, 1997) possibly lie between stroke features and radical units. However, it remains unclear whether logographemes are processed in serial with radical units or is processed in parallel with radical units. Since in current study, logographemes start to demonstrate effects at the N170 component similar to the time course of processing of radicals (Hsu et al., 2009; Su et al., 2012), this would suggest that logographemes are processed simultaneously with radicals at N170 component. Yet, other more visually related properties of logographemes, such as the number of logographeme demonstrated earlier ERP effects at the P100 component (Sar, 2014), implying that logographemes are processed earlier than radicals but also overlap in its processing time course. Since our findings cannot not allow us to make a strong claim of the logographeme effect at the N400 component, if logographemes could show an effect on N400 component like radicals (Hsu et al., 2009; Su et al., 2012), logographemes are more likely to be processed simultaneous or in parallel with radicals. Further research focusing on other logographeme properties, for example, evidence of logographeme position consistency, would be necessary for us to make stronger claims to further revise current character recognition models. Future research investigating effects of logographeme should aim to tease apart the effects between radical and logographeme activation and study the inter-related relationship between radical and logographemes.

In conclusion, this study provides some evidence from the effects of token frequency supporting logographemes as an existing basic unit in Chinese character processing that impacts on early visual-orthographic processing stages as reflected in the N170 component, but does not play a role in the early visual processing stage as reflected by P100 component and the mapping between orthography and phonology as well as later phonological processing as reflected by P200 component. Whether logographeme indeed affect in later semantic access or lexical-semantic competition would require further investigation.

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Appendix

Appendix 1. Grand average waveforms for the effects of logographeme type and token frequency at (1) P100, N170, (3) P200 and (4) N400 components in all target electrodes

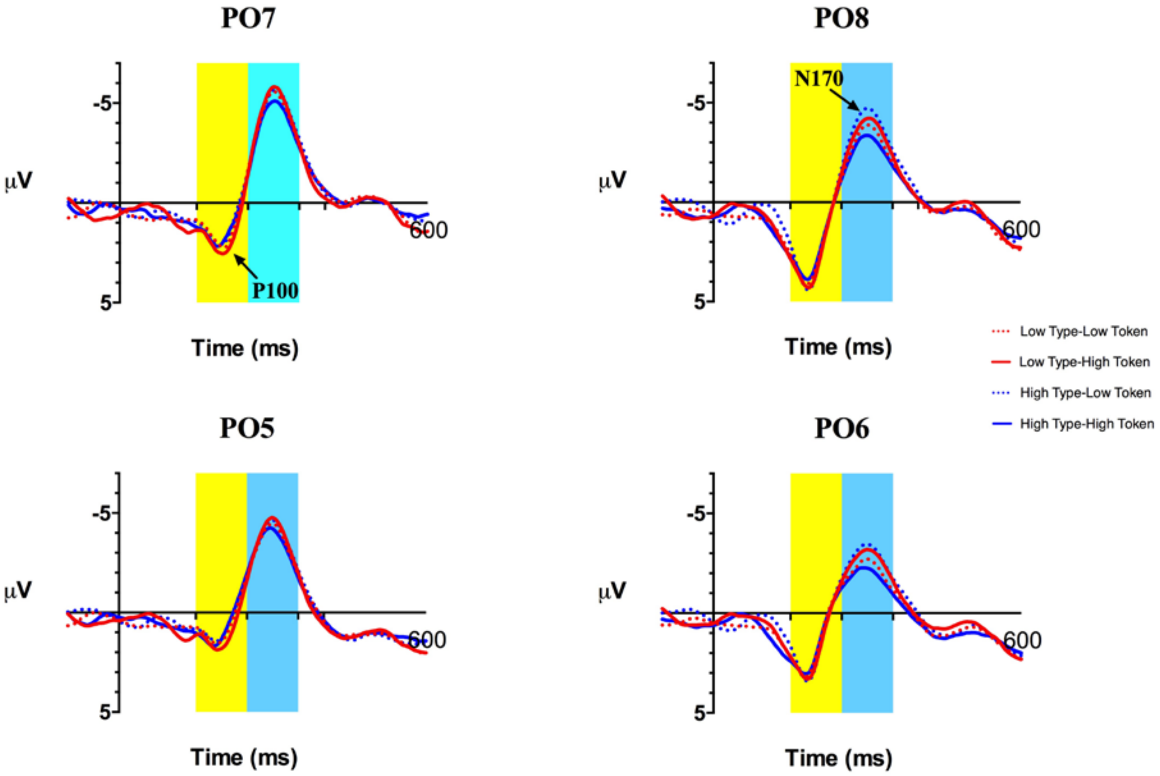


Figure 1. The P100 component is the positive deflection at 75-125ms (yellow area) while the N170 component is the negative deflection at 125-175ms (blue area) in electrodes PO5, PO6, PO7 and PO8

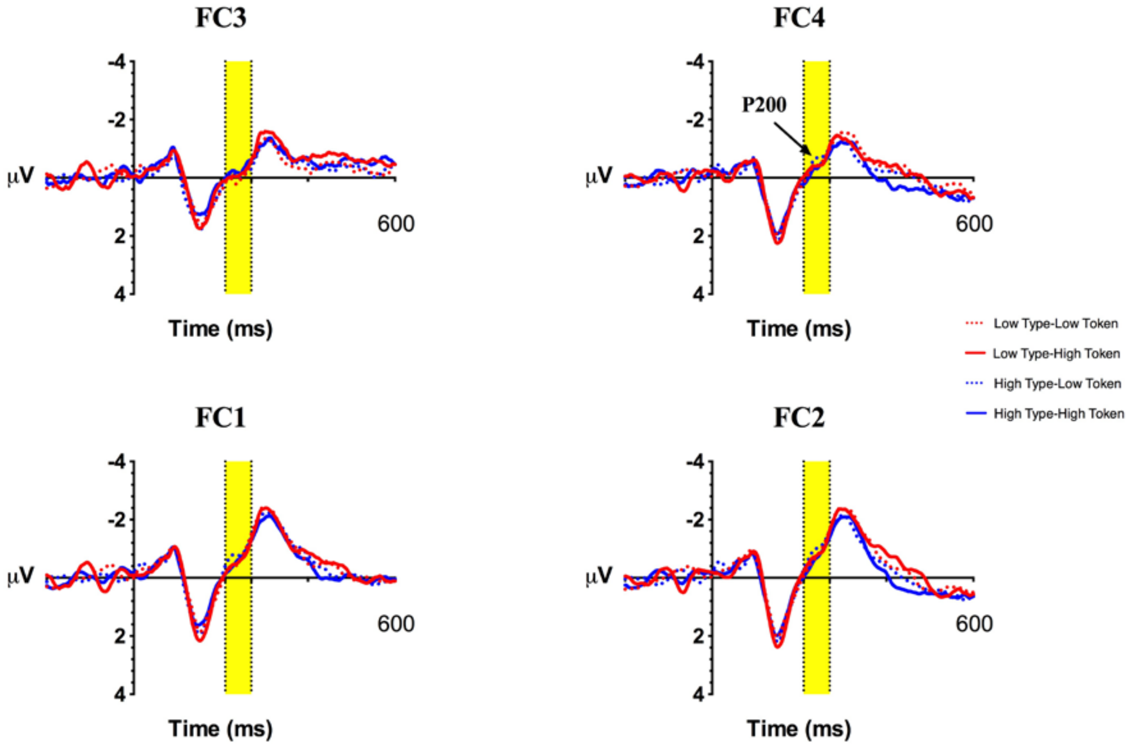


Figure 2. The P200 component is the positive-going peak at 210-270ms (yellow area) in electrodes FC1, FC2, FC3 and FC4

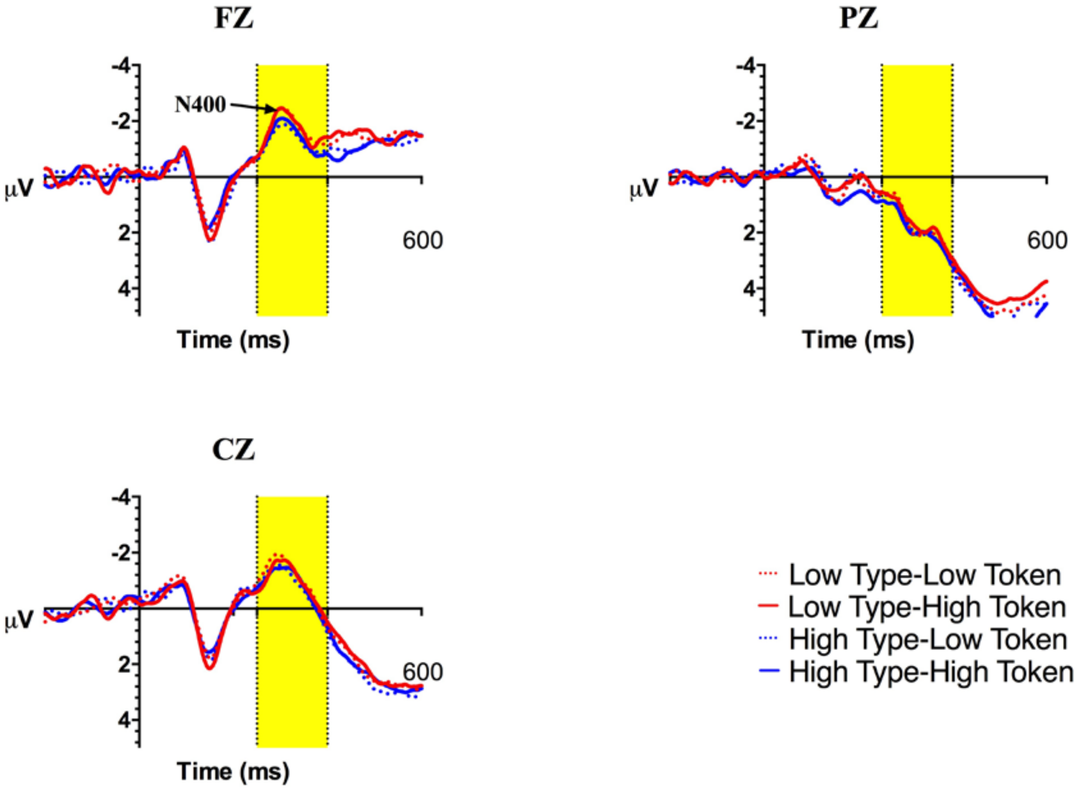
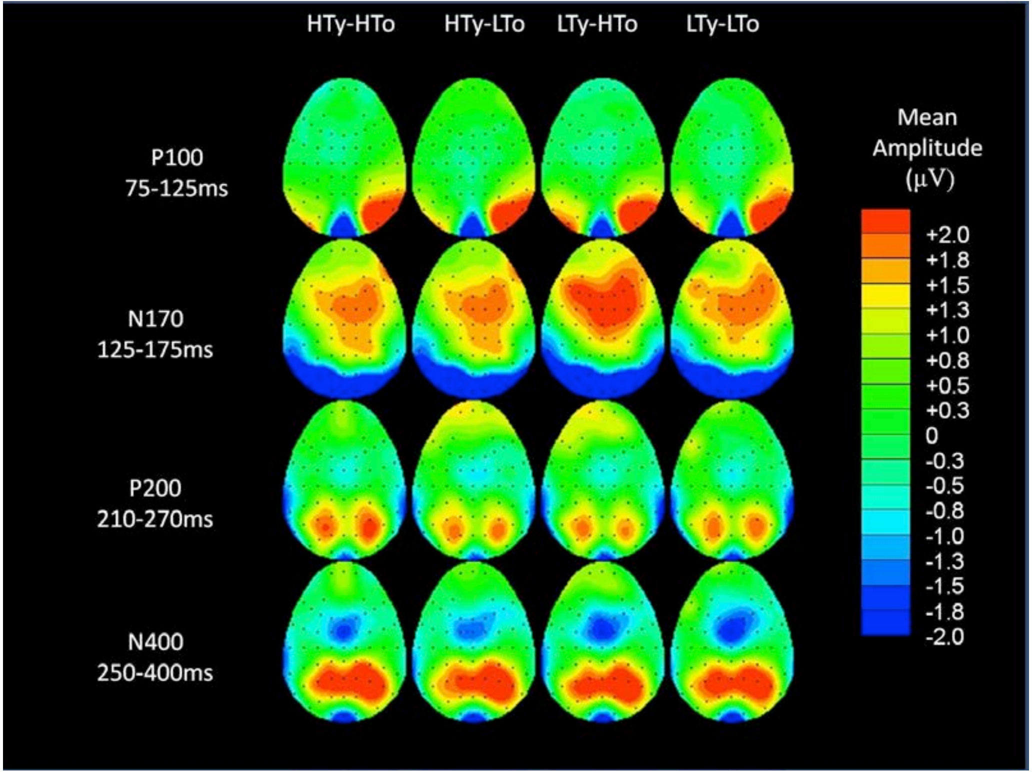


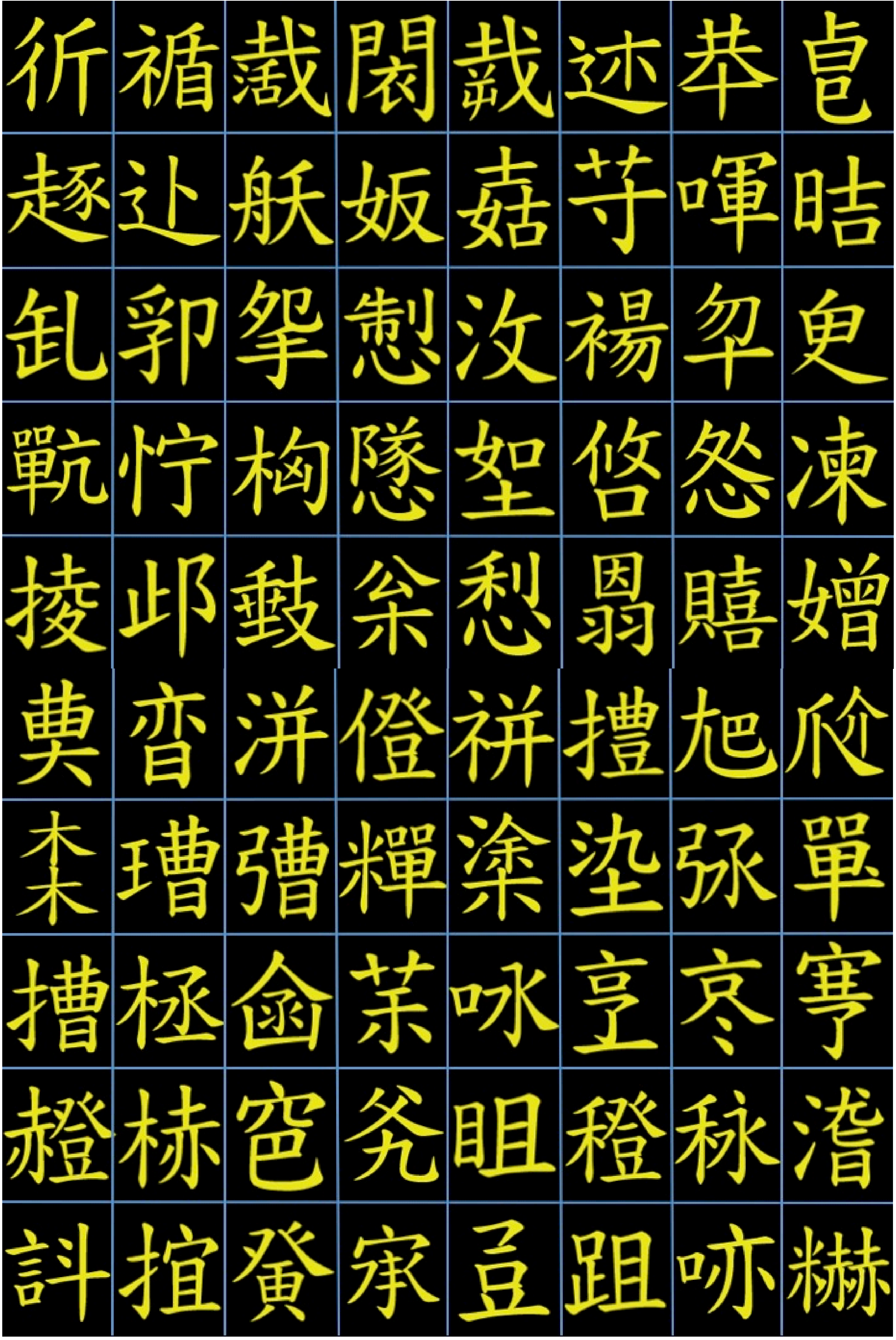
Figure 3. The N400 component is the negative peak at 250-400ms (yellow area) in electrodes FZ, CZ and PZ

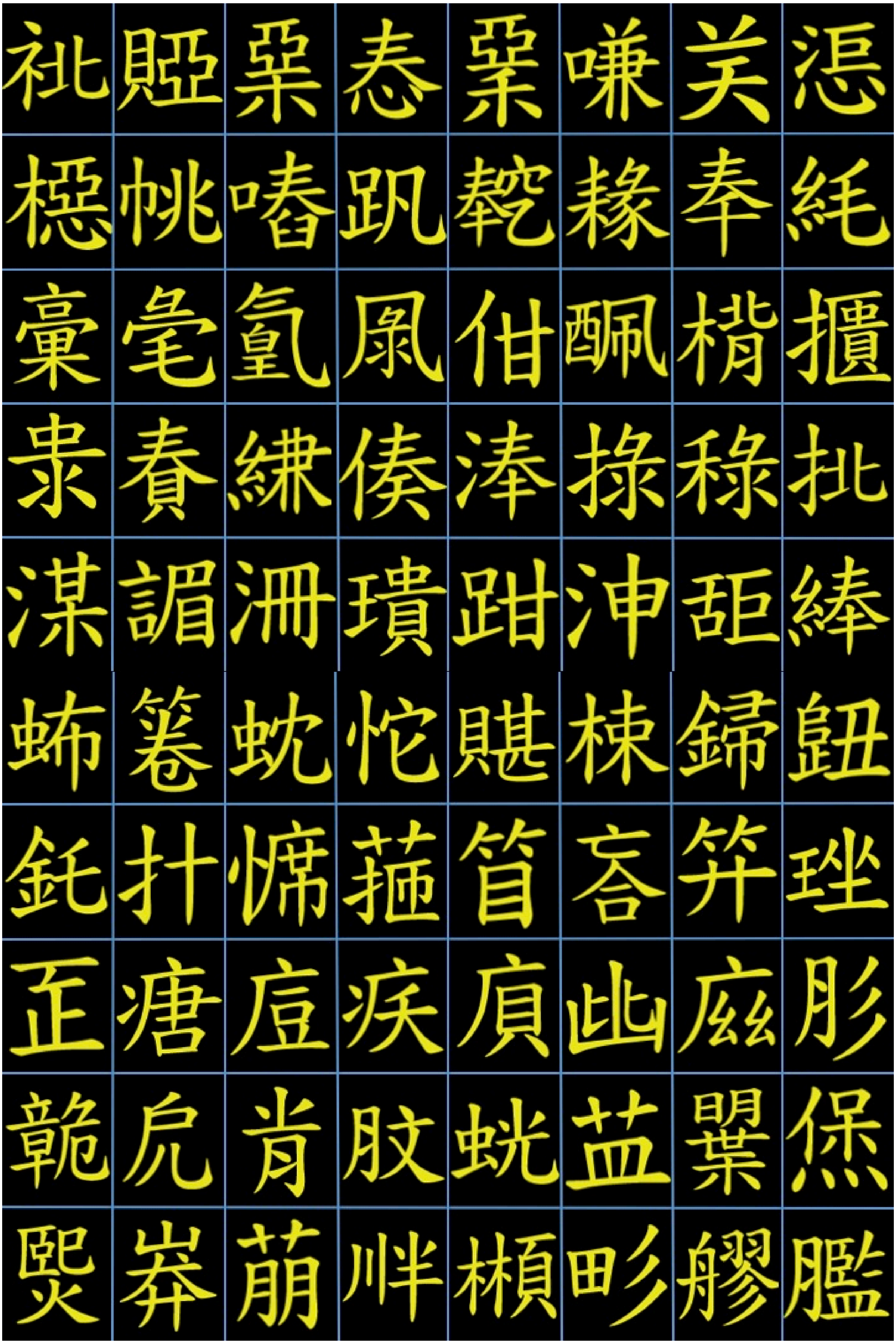
Appendix 2. Topographic plot of scalp distribution for logographeme type and token frequency at the P100, N170, P200 and N400 components (HTy: High Logographeme Type Frequency; LTy: Low Logographeme Type Frequency; HTo: High logographeme Token Frequency; LTo: Low logographeme token frequency)



Appendix 3. List of (1) pseudo and (2) real characters stimuli in the experiment

(1) Pseudo Characters





(b) Real Characters

High type-high token frequency condition

祈	卑	裁	栽	杭	卓	赴	循
舨	寺	桔	嬉	卸	逆	逐	怨
湯	匆	洶	墜	恕	妖	菇	咎
淩	悠	玫	歧	恩	梨	乳	郵
闊	巷	貯	翁	贈	揀	掣	暉

High type-low token frequency condition

蜷	蛇	蚊	怖	忱	悚	鈕	針
箍	答	笑	痘	症	崩	幽	脆
肩	畔	盟	艦	煲	熙	盲	湛
葉	托	頁	順	庇	唐	座	蓆
歸	彬	膠	彰	胱	光	弄	莽

Low type-high token frequency condition

曹	禮	糟	槽	嘈	併	拼	尬
稽	禪	彈	彈	塗	余	丞	承
拯	菡	哼	亨	赫	奕	嚇	跡
爬	爸	登	瞪	澄	橙	永	泳
寅	租	粗	誼	抖	寒	染	究

Low type-low token frequency condition

賺	兼	啞	挖	惡	惡	噁	跳
揹	乘	帆	凰	乖	佩	耗	毫
泰	秦	奏	捧	棒	俸	椿	湊
貴	距	潰	彙	渠	楣	櫃	緣
祿	珊	甜	謀	氣	酣	紳	綠