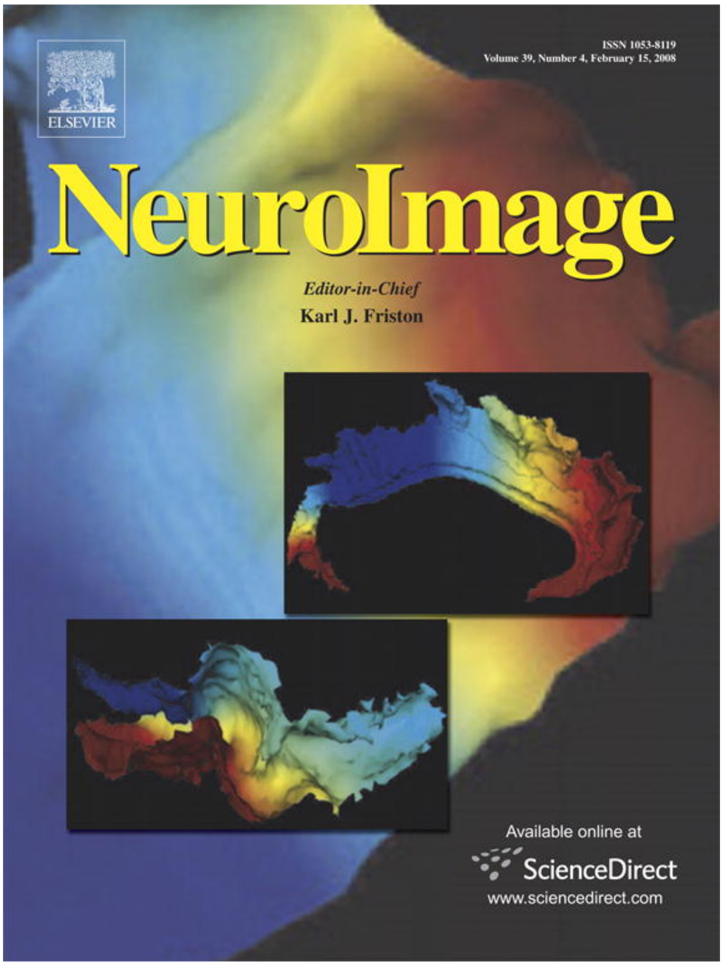
ISSN 1053-8119
Volume 39, Number 4, February 15, 2008
ELSEVIER
NeuroImage
Editor-in-Chief
Karl J. Friston
Available online at
ScienceDirect
www.sciencedirect.com

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 39 (2008) 2025 – 2037

Language experience shapes early electrophysiological responses to visual stimuli: The effects of writing system, stimulus length, and presentation duration

Gui Xue,[a,b,c,*] Ting Jiang,[d] Chuansheng Chen,[e] and Qi Dong[d,*]

[a]*Department of Psychology, University of Southern California, Los Angeles, CA 90089-1061, USA*
[b]*Dana and David Dornsife Cognitive Neuroscience Imaging Center, University of Southern California, Los Angeles, CA 90089-1061, USA*
[c]*Brain and Creativity Institute, University of Southern California, Los Angeles, CA 90089-1061, USA*
[d]*State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, PR China*
[e]*Department of Psychology and Social Behavior, University of California, Irvine, Irvine, CA 92697-7085, USA*

Received 1 June 2007; revised 23 September 2007; accepted 19 October 2007

How language experience affects visual word recognition has been a topic of intense interest. Using event-related potentials (ERPs), the present study compared the early electrophysiological responses (i.e., N1) to familiar and unfamiliar writings under different conditions. Thirteen native Chinese speakers (with English as their second language) were recruited to passively view four types of scripts: Chinese (familiar logographic writings), English (familiar alphabetic writings), Korean Hangul (unfamiliar logographic writings), and Tibetan (unfamiliar alphabetic writings). Stimuli also differed in lexicality (words vs. non-words, for familiar writings only), length (characters/letters vs. words), and presentation duration (100 ms vs. 750 ms). We found no significant differences between words and non-words, and the effect of language experience (familiar vs. unfamiliar) was significantly modulated by stimulus length and writing system, and to a less degree, by presentation duration. That is, the language experience effect (i.e., a stronger N1 response to familiar writings than to unfamiliar writings) was significant only for alphabetic letters, but not for alphabetic and logographic words. The difference between Chinese characters and unfamiliar logographic characters was significant under the condition of short presentation duration, but not under the condition of long presentation duration. Long stimuli elicited a stronger N1 response than did short stimuli, but this effect was significantly attenuated for familiar writings. These results suggest that N1 response might not reliably differentiate familiar and unfamiliar writings. More importantly, our results suggest that N1 is modulated by visual, linguistic, and task factors, which has important implications for the visual expertise hypothesis.

Keywords: Chinese; Event-related potentials; Language; Language experience; N1; N170; Writing system; Visual expertise; Visual word recognition

Introduction

Learning to read is accompanied by significant behavioral changes such as increased processing speed and attenuated or diminished effect of stimulus length (Perfetti and Hogaboam, 1975; Reicher, 1969; Weekes, 1997). Neural changes associated with reading acquisition have also been well documented under both natural (e.g., Brem et al., 2006; Burgund et al., 2006; Maurer et al., 2005b, 2006) and experimental conditions (e.g., Brem et al., 2005; Chen et al., 2007; McCandliss et al., 1997; Perfetti et al., 2005; Xue et al., 2006). Nevertheless, there is little consensus with regard to the exact mechanisms underlying these neural changes. Researchers have been debating about the degree to which these changes reflect increased visual expertise with a particular writing system, and about the specific underlying neural indices of such expertise (e.g., McCandliss et al., 2003; Xue et al., 2006).

Two types of common techniques, namely neurophysiology (e.g., ERPs and MEG) and functional imaging (e.g., fMRI and PET), have been used to explore the neural mechanisms of reading acquisition. Using functional imaging techniques, researchers have mainly studied whether the left midfusiform area, the so-called visual word form area (VWFA), is specific to the processing of visual word forms and whether years of reading experience increase its sensitivity to visual word forms (Cohen and Dehaene, 2004; Price and Devlin, 2003; Xue et al., 2006). With ERPs and MEG, researchers have primarily explored whether the first negative component with a latency around 150–200 ms localized in the occipito-temporal cortex (i.e., N1) is more sensitive to visual words than to other visual objects (Barber and Kutas, 2007; Maurer et al., 2005b). For both techniques, the important theoretical question is whether these differences, if they exist, could be attributed to visual expertise. In the present study, we focused on neurophysiological studies.

* Corresponding authors. G. Xue is to be contacted at Department of Psychology, University of Southern California, Los Angeles, CA 90089-1061, USA. Fax: +1 213 821 4270.

E-mail addresses: gxue@usc.edu (G. Xue), dongqi@bnu.edu.cn (Q. Dong).
Available online on ScienceDirect (www.sciencedirect.com).

1053-8119/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2007.10.021

N1 and visual word form processing

N1, also known as N170, is characterized by the first negativity at bilateral occipito-temporal electrodes and the central positivity at the fronto-parietal electrodes. It has been consistently revealed within a latency between 150 and 200 ms, in all types of object processing, including words, faces, tools, and so on (e.g., Schendan et al., 1998). Source localization indicated relatively hemispheric specificity between words and faces, with left-hemisphere dominance for words and right-hemisphere dominance for faces (Rossion et al., 2003).

N1 has been proposed to be an index of expertise in object recognition. For example, compared to other objects, a stronger N1 response has been revealed when car experts are processing pictures of cars (Tanaka and Curran, 2001), and bird experts are processing pictures of birds (Gauthier et al., 2003). People who were trained to be experts of birds (Scott et al., 2006) or of novel objects (e.g., 'Greeble') (Rossion et al., 2002) also showed a stronger N1 to those training materials. A recent monkey study also showed an increased N1 response to familiar objects as opposed to novel objects (Peissig et al., 2007). Similarly, in the area of visual word recognition, it has been posited that reading experience increases visual expertise of a given writing system, and the enhanced N1 response to that writing compared to simple symbols might reflect a "coarse" specialization of N1 in visual word processing (Brem et al., 2005; Maurer et al., 2005a,b, 2006; Wong et al., 2005).

Many ERP studies have been conducted to examine the sensitivity or specialization of N1 in visual word processing. So far, researchers have compared native words/letters with false fonts (Eulitz et al., 2000; Schendan et al., 1998; Wong et al., 2005), symbols (Brem et al., 2006; Brem et al., 2005; Gros et al., 2002; Maurer et al., 2005b; McCandliss et al., 1997; Moscoso del Prado Martin et al., 2006; Tarkiainen et al., 2002, 1999), foreign writings (Huang et al., 2004; Pernet et al., 2003; Wong et al., 2005), letter strings (Bentin et al., 1999; Cohen et al., 2000; Martin et al., 2006; Proverbio et al., 2004), pseudowords (Proverbio et al., 2004; Shirahama et al., 2004; Wydell et al., 2003), and second-language words/letters (Liu and Perfetti, 2003; Wong et al., 2005). Furthermore, there was a study that compared native and foreign speakers on the same stimuli (Proverbio et al., 2006). The results were mixed: Some studies revealed a stronger N1 response for native words/letters than for other stimuli, but it was also common to see a lack of differences or even reversed patterns of differences (see Table 1). Such inconsistent results point to the possibility that the effect of language experience on the N1 response may be modulated by factors that varied across previous studies. Such factors include, but are not limited to, the experimental tasks (e.g., passive vs. active, perceptual vs. lexical), materials (e.g., letters vs. words, false fonts vs. foreign writings, alphabetical vs. logographic orthography), and stimulus presentation parameters (e.g., short vs. long duration, masked vs. unmasked). In order to have a comprehensive understanding of the relation between the N1 response and language experience, it is imperative to systematically investigate the potential moderators of that relation. Such an investigation could also help to describe the characteristics of N1 and elucidate its underlying cognitive mechanisms.

The present study examined language experience (familiar vs. unfamiliar writings) and lexicality effect (words vs. non-words) across different types of stimuli and experimental conditions, including alphabetic vs. logographic writing systems, short vs. long stimulus length, and short vs. long stimulus presentation duration. First, we review the literature on these potential moderators.

The effect of writing system

One factor that has received little attention is writing system. Writing systems differ greatly in their visual features. Logographic (e.g., Chinese) and alphabetic writing systems (e.g., English) provide a good illustration of this contrast. For example, relatively consistent differences have been reported in the primary visual system, with Chinese showing more bilateral activation and English showing more leftward asymmetry (Xue et al., 2005). But how different orthographies affect word sensitivity remains obscure. Though several studies on alphabetic languages reported word sensitivity in the left fusiform cortex (e.g., Cohen et al., 2002; Polk and Farah, 2002), two recent fMRI studies revealed no word sensitivity in this region for either native Chinese or English speakers when their native language was compared to logograph-like foreign characters, i.e., Korean Hangul (Xue et al., 2006; Xue and Polrack, 2007). Presumably, the compact and complex visual pattern of logographic characters requires extensive visual analysis and thus reduces its differences with native writings. In the present study, this hypothesis was examined by comparing the N1 response to logographic and alphabetic unfamiliar writings, and by examining word sensitivity in logographic and alphabetic writing systems.

The effect of stimulus length

Another important factor that affects N1 is word length. Behaviorally, it has been repeatedly shown that high-frequency words of different lengths are processed at a comparable speed (i.e., no word length effect), whereas low-frequency words and non-words showed the word length effect (Weekes, 1997). Such results are consistent with the notion that high-frequency words, but not low-frequency words and non-words, are processed holistically (but see Pelli et al., 2003). Several studies have examined the effect of stimulus length on the N1 response, but no clear picture has been obtained. For example, some researchers have found a stronger N1 response to longer stimuli than to shorter stimuli (Wong et al., 2005; Wydell et al., 2003) whereas others found no differences on P150 at the parietal electrodes (Schendan et al., 1998), the equivalent of N1 observed at the posterior electrodes. Several studies have further revealed a stronger ERP response to longer words at around 100 ms (Assadollahi and Pulvermuller, 2001; Hauk et al., 2006; Hauk and Pulvermuller, 2004), but a reversed pattern after 150 ms (Hauk and Pulvermuller, 2004). The word length effect has also been reported in a later time window, again with mixed results (see Hauk and Pulvermuller, 2004 for a review).

These mixed effects may have been exacerbated by the use of both lexical (e.g., Hauk and Pulvermuller, 2004) and non-lexical materials (e.g., Wong et al., 2005). Wydell et al. (2003) found similar length effects for words and non-words at around 100 ms, but stronger length effects for non-words after around 200 ms. Moreover, significant differences in other experimental parameters, including stimulus presentation and task requirements might contribute to these different findings. The present study addressed this issue by examining the length-by-language (familiar vs. unfamiliar writings) interaction under the same experimental conditions.

The effect of presentation duration

Although a wide variety of presentation durations have been used in the literature to examine the visual expertise hypothesis (see Table 1), surprisingly few studies have attempted to directly examine its effect on the N1 response. In one study (Martin et al., 2006), words and non-words were presented for 50 ms or 66 ms, and a stronger and faster (i.e., shorter peak latency) N1 response was found under the short duration condition than under the long duration condition for both types of stimuli. There was a significant duration-by-stimulus interaction: That is, there was a significant difference between words and non-words at the 66 ms duration but not at the 50 ms duration. This clearly suggests that presentation duration is an important factor for word sensitivity. So far, most studies used either a short duration of about 100 ms or less, or a long duration of 750 ms or longer, but there were no direct comparisons between these two conditions.

The importance of presentation duration is further supported by PET and fMRI studies. Studies with a 150 ms or shorter duration generally reported more activation for words and word-like stimuli, whereas studies with a duration as long as 750 ms did not show such a pattern (Indefrey et al., 1997) and sometimes showed a reversed pattern (Xue et al., 2006). In two PET studies (Price et al., 1996, 1994), Price and her colleagues systematically explored the effect of presentation duration on word processing. In one study (Price et al., 1994), they used a word-reading task with presentation durations of 150 ms and 1000 ms and used false fonts for the baseline condition. They found that the shorter duration was associated with stronger activations in the left medial fusiform area and the posterior temporal lobe. The other PET study used resting condition as the baseline, and found that activation in the fusiform cortex increased with the longer duration (Price et al., 1996). These results seem to imply a stimulus-by-duration interaction in modulating the activation in the visual system: That is, with the increase of presentation duration, false fonts show more response increase than do words. This possible interaction was examined with ERP in the present study.

Taken together, existing results suggest that the N1 response is modulated by a number of physical, lexical, and learning factors. However, a clear and consistent picture has not been obtained. The apparent differences in experimental details, including the task requirements, data acquisition, and analysis, may simply have exaggerated the discrepancies in results. Moreover, little effort has been made to include all these factors in one study and examine their possible interactions. It is thus necessary to take an integrative approach to examining all these factors within the same methodological framework.

The present study adopted such an approach. Chinese college students who had been learning English as their second language for more than 6 years were asked to passively view four types of scripts: Chinese (familiar logographic writings), English (familiar alphabetic writings), Korean Hangul (unfamiliar logographic writings), and Tibetan (unfamiliar alphabetic writings). To examine the effects of stimulus length, in addition to single characters and letters, non-words were constructed, with two characters in the logographic writings and three letters in the alphabetic writings. For Chinese and English, non-words were compared to visually matched words to examine the effect of lexicality. Each type of stimuli was presented for 100 ms and 750 ms to examine the effect of presentation duration. We were interested in both the main effects of these factors (i.e., stimulus length, presentation duration, and writing system) on N1 as well as the interactions among these factors.

Methods

Participants

Sixteen undergraduate subjects were recruited from Beijing Normal University for this study. All participants were right-handed and had normal eyesight in both eyes. They had been learning English as second language since middle school (>6 years) and had self-reportedly attained a medium level of English fluency. Three subjects were removed from analysis due to substantial eye blink artifacts or signal drift. The remaining 13 subjects (7 males) had a mean age of 22.6 years (ranged from 20 to 27 years). Subjects gave written informed consent before the experiment.

Materials

Ten types of materials were used in this study (see Fig. 1). The five logographic stimuli included Chinese words (CW), Chinese non-words (CNW), Chinese characters (CC), unfamiliar logographic (i.e., Korean Hangul) words (ULW), and unfamiliar logographic characters (ULC). The five alphabetic stimuli included English words (EW), English non-words (ENW), English letters (EL), unfamiliar alphabetic (i.e., Tibetan) words (UAW), and unfamiliar alphabetic letters (UAL). Each category, except for EL and UAL, had 120 stimuli, which were divided into two matched groups for the short- (i.e., 100 ms) and long-duration presentation (i.e., 750 ms) conditions, and counterbalanced across subjects. Only twenty ELs and UALs were used and repeated three times in each condition. The selection criteria for each type of stimuli are detailed below.

All Chinese characters (CC) were high-frequency characters (higher than 90 per million according to the Chinese word frequency dictionary) (Wang and Chang, 1985), with 3–10 strokes, and 2–3 units according to the definition by Chen et al. (1996). The ULCs were strictly matched with Chinese characters in visual complexity (i.e., number of strokes and units). The Chinese words (CW) were all high-frequency words, with each character complying with the above criteria. To construct the Chinese non-words (CNW), 240 different characters according to the above criteria were selected and randomly paired. Pairs were replaced if they (e.g., AB) or the reversed pattern (i.e., BA) were real words, or homophones of real words. These stimuli were further evaluated by five research assistants in the laboratory to make sure they did not elicit clear meanings (i.e., no items scored more than 2 on a 5-point scale with 1 representing "meaningless" and 5 representing "meaningful"). Because the subjects in the present study could not read Korean, the ULWs were random combinations of two different Korean Hangul characters selected based on the above criteria regarding visual complexity. Visual complexity of each character was strictly matched across the five visual categories and the two experimental conditions. The word frequency of Chinese characters was also matched across conditions.

Twenty English letters (excluding all vowels and the letter "Y") and twenty Tibetan letters were selected. Tibetan letters were visually dissimilar to English letters and other scripts familiar to the subjects (e.g., Roman numerals). All English words (EW) were high-frequency 3-letter words chosen from MRC Psycholinguistic

Table 1
Summary of studies examining the language experience effect in the N1 response [a]

Study	Reference	EQUIP	Materials	Task(s)	Stimulus Dur/ISI	Measures	Results
1	Bentin et al., 1999	EEG	French words, PWs, CSs, symbols, forms	Size oddball	500 ms/750 ms	Mean amplitude (T5/6, 1/2, PO3/4, OM1/2): ±48 ms around the peak	Words = PWs = CSs > symbols = forms
2	Brem et al., 2005	EEG	German words and symbols	One-back	700 ms/1370 ms, jittered	GFP: 148–160 ms	Words > symbols
3	Brem et al., 2006	EEG	German words and symbols	One-back	700 ms/540 ms, jittered	GFP: 132–182 ms	Words = symbols [b]
4	Eulitz et al., 2000	MEG	German words, false fonts, shapes, dots	Feature detection	400 ms/jittered from 2 to 2.4 ms	Mean amplitude (ERF of M180): 160–220 ms	Words = false fonts > dots = shapes
5	Gros et al., 2002	EEG	English letters, geometric figures, letter "O", circles	Passive viewing	1s/2 s	Mean amplitude (O1/2; PO3/4; P3/4; P7/8; CP5/6): 140–200 ms	Figures > letters; Circle "O" = letter "O"
6	Khateb et al., 2002	EEG	French words, PWs, pictures, scrambled pictures	Recognition: know or not	130/1300 ms	N150 (F1/3, F2/4, Fz, PO7/8, PO3/4, POz)	Similar response for all four types of stimuli [c]
7	Martin et al., 2006	EEG	French words and consonant strings	Raichel – Wheel paradigm	50 or 66 ms duration, masked	Peak amplitude (O1/2, PO3/4, PO7/8, P5/6) : 150–240 ms	50 ms: Words = CSs 66 ms: Words > CSs
8	Maurer et al., 2005a	EEG	English words, PWs and symbols	One-back	700 ms/1350 ms	GFP and Amplitude (occipito-temporal channels) (144–248 ms)	GFP: Symbols > PWs = words; Amplitude: Words > PWs > symbols
9	Maurer et al., 2005b	EEG	German words, PWs, symbols, pictures	One-back	700 ms/1350 ms	GFP and peak (T5/6)	Words = PWs > symbols
10	McCandliss et al., 1997	EEG	English words, PWs, CSs	Passive viewing; feature detection	765 ms/self-paced	Mean amplitude (P1/2, P3/4, P5/6): 170–230 ms	CSs > PWs > Words
11	Moscoso del Prado Martin et al., 2006	EEG	English words, hash marks	Silent reading	100 ms/jittered from 2 to 3 s	RMS: 144–164 ms; Norm current estimates	RMS: hash marks > words; Norm current estimates: words > hash marks over left fusiform; hash mark > words over right occipital

12	Nobre et al., 1994	Cortical recording	English words, PWs, non-words	Semantic target detection	500 ms/2–2.1 s	N200 at posterior fusiform (O1/2, P7/8, CP5/6)	Similar across all string types
13	Pernet et al., 2003	EEG	Letters, tools, geometric shapes, faces, Asiatic characters, structured texture	Target detection	100 ms/3 s	Mean amplitude (CP5/6, P7/8, O1/2): around 180 ms	Asiatic characters > others > faces (no difference with MANOVA)
14	Proverbio et al., 2004	EEG	Italian words, PWs, CSs	Target phoneme detection	1000 ms/1.4–1.6 s	Mean amplitude (O1/2, OL/OR, T5/6): 140–180 ms	Words = PWs = CSs
15	Proverbio et al., 2006	EEG	Greek words and PWs	Target letter detection	650 ms/1.3–1.7 s	Mean amplitude (OL/OR): 140–190 ms	Greek readers > native Italian readers
16	Schendan et al., 1998	EEG	English words, non-words, false fonts, icon strings, objects, pseudo-objects	Target detection	800 ms/2.6–3 s	Mean amplitude of P150 (Cz): (125–175 ms)	Words = non-words = false fonts > icon strings > objects; Objects > pseudo-objects at lateral but not midline sites
17	Shirahama et al., 2004	MEG	Kana, Kanji, Kana PWs, symbols	Semantic target detection	1.2 s/0.3–0.5 s	RMS: 150–250 ms	Kana = Kana PWs = Kanji > symbols
18	Tarkiainen et al., 1999	MEG	Finish letters, syllables, words, symbols	Question mark detection	60 ms/2000 ms	ECDs: around 143 ms	Letters > symbols
19	Wong et al., 2005	EEG	Roman letters, Chinese characters, pseudo-fonts and their string version	One-back	750 ms/500 ms, jittered	Peak amplitude (T5/6 to O1/2): N170 within the time window of 120 to 250 ms	English speakers: Roman > Chinese = pseudo-fonts; Chinese–English bilinguals: Chinese = Roman > pseudo-fonts
20	Wydell et al., 2003	MEG	Finnish words, non-words in two different lengths	Question mark detection	400 ms/2600 ms	Peak amplitude (occipital, midline): within 200 ms	Words = non-words

Abbreviations: EQUIP, equipment; Dur, duration; ISI: inter-stimulus interval; PW: pseudoword; CS: consonant string; GFP: global field power; RMS: root mean squares; ECD: equivalent current dipoles. ">": stronger negativity; "=": no significant difference.

[a] This table includes ERP and MEG studies that presented results related to the language experience effect. The inclusion criteria were: (1) using adult subjects; (2) using a pure visual task, including passive viewing (with a feature detection task to assure attention) or visual comparison; (3) comparing words or PW with other visual symbols, like non-words, foreign writings, false fonts, geometry shapes, and simple symbols; or comparing native and foreign readers. Results from developmental studies and training studies were not included here but are discussed in the text.

[b] They found a significant difference between words and symbols at the late N1 response (183–256 ms post stimulus) for adolescents, but not for adults.

[c] No quantification or statistical comparison was available.

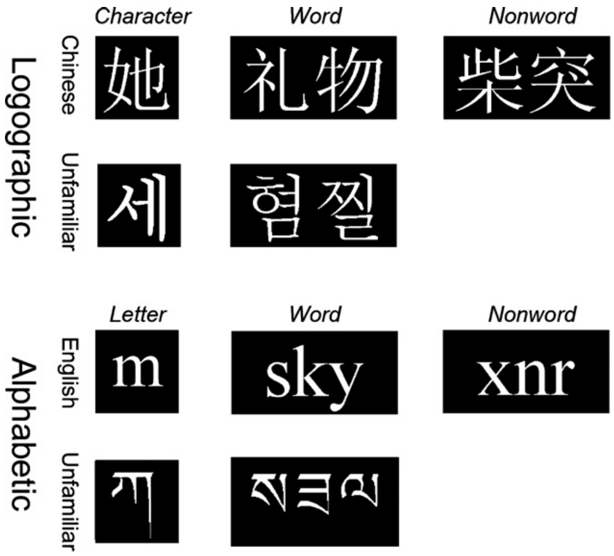

Fig. 1. Examples of stimuli used in the present experiment.

database. Because the frequency statistics might not apply to Chinese speakers for whom English is only a second language, five undergraduate students with a similar level of English fluency as the subjects were asked to evaluate the familiarity of these English words on a 5-point scale with 1 representing "never seen it before" and 5 representing "very familiar." Words with a mean score less than 4 were excluded. Because the subjects could not read Tibetan, UAWs were created by randomly combining three different Tibetan letters. Three-letter ENWs were also created randomly.

It should be noted that the Korean and Tibetan words used in the present study should be functionally equivalent to Korean and Tibetan non-words because the subjects did not know these languages. Nevertheless, they were so named to facilitate the comparisons with real words in Chinese and English.

Procedure

Subjects were seated 105 cm away from the computer screen in a dimly lit, sound-attenuated room. A passive viewing task was adopted to reduce the effect of higher-level task requirements and possible strategic differences between familiar and unfamiliar writings in the comparison task. All stimuli were presented visually in white against black background at the center of the screen. The logographic stimuli (300 trials in total) and alphabetical stimuli (also 300 trials) were presented in separate sessions to reduce the length of each session. Both alphabetic and logographic stimuli were presented with two presentation durations: a long- and a short-duration condition. In other words, there were four separate sessions: alphabetic stimuli/long duration, alphabetic stimuli/short duration, logographic stimuli/long duration, and logographic stimuli/short duration. Within each session, all stimuli (familiar letters/characters, familiar words, familiar non-words, unfamiliar letters/characters, and unfamiliar words) were randomly presented. This design allowed us to directly examine the critical contrast (familiar vs. unfamiliar writings, words vs. non-words, and letters/characters vs. words) within one session. For each trial, the stimulus (151×151 pixels for letters and characters, and 302×151 pixels for words and strings) was presented for 750 ms (i.e., the long-duration condition) or 100 ms (i.e., the short-duration condition), followed by a blank screen for 1250 ms or 1900 ms, respectively. Random time delay (i.e., "jitter"), created according to the exponential distribution (mean: 500 ms, range from 6 ms to 3000 ms), was added to the end of each trial to reduce the effect of expectation. Subjects were asked to fixate on the screen and passively view these stimuli during the whole session. To guarantee subjects' attention, for 5% of the trials (i.e., 15 trials in each session), a picture was flashed (100 ms duration) shortly after the writings (100 ms delay). Subjects were required to judge whether the picture depicted was an animal or an object by pressing one of two buttons. These trials were excluded from analysis. A 3-s blink symbol ("~ ~") appeared every four trials signaling that subjects could blink their eyes. The next trial began after an interval of 1 s. Subjects took a short break of 1–2 min in the middle of each session and resumed the task by pressing a button. They took a longer rest between two sessions. The order of the four sessions was counterbalanced across subjects.

Before the formal test, subjects were presented 20 practice trials. During the practice period, subjects were instructed to avoid eye-blinks within a trial. Subjects were given feedback if they blinked, made a wrong response, or had obvious head movements.

Electroencephalogram (EEG) recording and analysis

Scalp voltages were recorded by a NeuroSCAN system, using a 64-channel Quick-cap with silver chloride electrodes (Neurosoft, Inc. Sterling, USA). The impedance of all electrodes was kept below 5 kΩ. Linked ears served as reference, and the middle of the forehead served as ground. Two channels were placed at the outer canthi of both eyes to record the horizontal electrooculogram (HEOG), another two channels above and below the left eye for vertical electrooculogram (VEOG). Electroencephalogram (EEG) was amplified on-line with a high-pass frequency filter of 0.05 Hz and a low-pass frequency filter of 100 Hz. The sampling rate was 1000 Hz.

The continuous EEG was transformed to the average reference (Lehmann and Skrandies, 1980). Trials were rejected for movement artifacts, eye movements, blinks, or amplifier saturation. Trials with artifacts exceeding ± 100 μV were also excluded. The remaining trials were averaged for each type of stimuli separately for each subject. Due to our special effort to minimize the eye-blink artifacts, the valid trials used for averaging were 48 for each type of stimuli. The continuous EEG data were segmented into epochs from 200 ms pre-stimulus until 800 ms post-stimulus. The 200 ms pre-stimulus served as the baseline, which had been subtracted out before grand average. Averaged waveform was filtered with a low-pass filter of 30 Hz (zero-phase, 12 dB/octave). The grand average was obtained by averaging across subjects' averages separately for each type of stimuli. Scalp topographies were visualized with EEGLAB (http://sccn.ucsd.edu/eeglab/).

N1 quantification and statistical analysis

Based on visual inspection of each subject's data, N1 was identified as the first visible negative peak 120–180 ms post-stimulus in occipito-temporal lobe. Because the N1 response was most obvious in PO5 and PO6, further data quantification and statistical analysis focused on these two electrodes. The mean amplitude of N1 was calculated for an epoch comprising 20 time points (20 ms), 10 before and 10 after the peak for each type of stimuli, based on the grand mean response (the center of time windows identified for each condition was summarized in Table 2).

Table 2
The peak latency (ms) of N1 (PO5 and PO6) identified for each condition based on grand mean ERP responses

Electrodes	Logographic		Alphabetic	
	PO5	PO6	PO5	PO6
Long presentation duration (750 ms)				
Familiar letters/characters	156	156	158	156
Unfamiliar letters/characters	170	167	158	158
Familiar non-words	151	148	159	153
Familiar words	152	147	152	154
Unfamiliar words	161	153	152	150
Short presentation duration (100 ms)				
Familiar letters/characters	156	155	158	156
Unfamiliar letters/characters	170	168	158	156
Familiar non-words	151	149	159	158
Familiar words	151	148	156	154
Unfamiliar words	157	158	150	149

A series of within-subject repeated-measures ANOVA was conducted to examine the effects of experimental factors. Unless otherwise noted, within-subject standard error is reported (Loftus and Masson, 1994). Due to our focus on the sensitivity hypothesis, no further statistical analysis was conducted on the peak latency.

Results

Overall, the early N1 and P1 responses to all stimulus types occurred at a latency of around 150–170 ms. The topographic map at 120–180 ms post-stimulus for each type of stimuli is shown in Fig. 2. ERPs from selected 10–20 locations with the strongest N1 response (i.e., PO5 and PO6) are shown in Fig. 3 (for logographic writings) and Fig. 4 (for alphabetic writings).

The effect of lexicality

In the first analysis, we examined the lexicality effect by testing whether words and non-words showed different N1 responses. Three-way ANOVA with lexicality (words vs. non-words), duration (short vs. long), and hemisphere (left vs. right) as within-subject factors were conducted for Chinese and English materials separately (Fig. 5). (Lexicality effect was not examined for unfamiliar writings because the subjects did not know those languages.) Results showed no significant differences between Chinese words and non-words [$F(1,12)=.004$, $p=.948$], nor between English words and non-words [$F(1,12)=.85$, $p=.375$]. Also, there was no effect of presentation duration or hemisphere, nor were there any significant interactions (all p values >.133).

The effect of language experience

The second analysis was conducted to examine the N1 effects in both hemispheres (left vs. right) of language experience (familiar vs. unfamiliar writings), stimulus length (letters/characters vs. words), presentation duration (long vs. short), and writing system (alphabetic vs. logographic). A five-way ANOVA with the above-mentioned variables as within-subject factors was conducted. Results are shown in Fig. 6.

This analysis revealed significant main effects of language experience [$F(1,12)=12.207$, $p=.004$] and stimulus length [$F(1,12)=14.187$, $p=.003$]. In addition, there was a significant interaction between language experience and stimulus length [$F(1,12)=10.424$, $p=.007$], a significant three-way interaction among language experience, stimulus length, and writing systems [$F(1,12)=12.221$, $p=.004$], and a marginally significant four-way interaction among stimulus length, hemisphere, language experience, and presentation duration [$F(1,12)=4.070$, $p=.066$]. No other main effects or interactions were significant (all p values >.16).

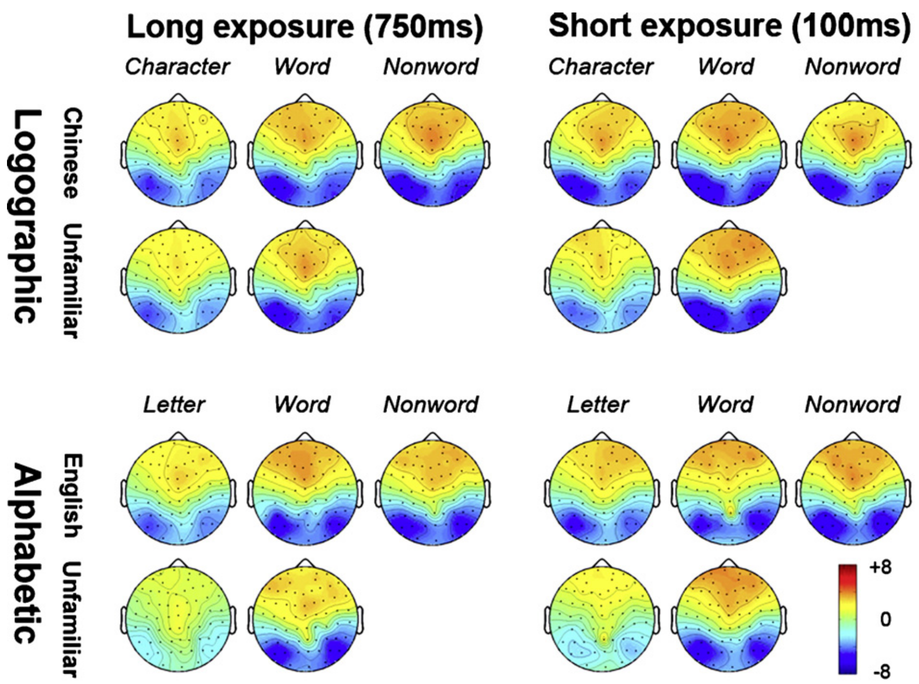

Fig. 2. Topographic distribution of the N1 response (120–180 ms) for different conditions.

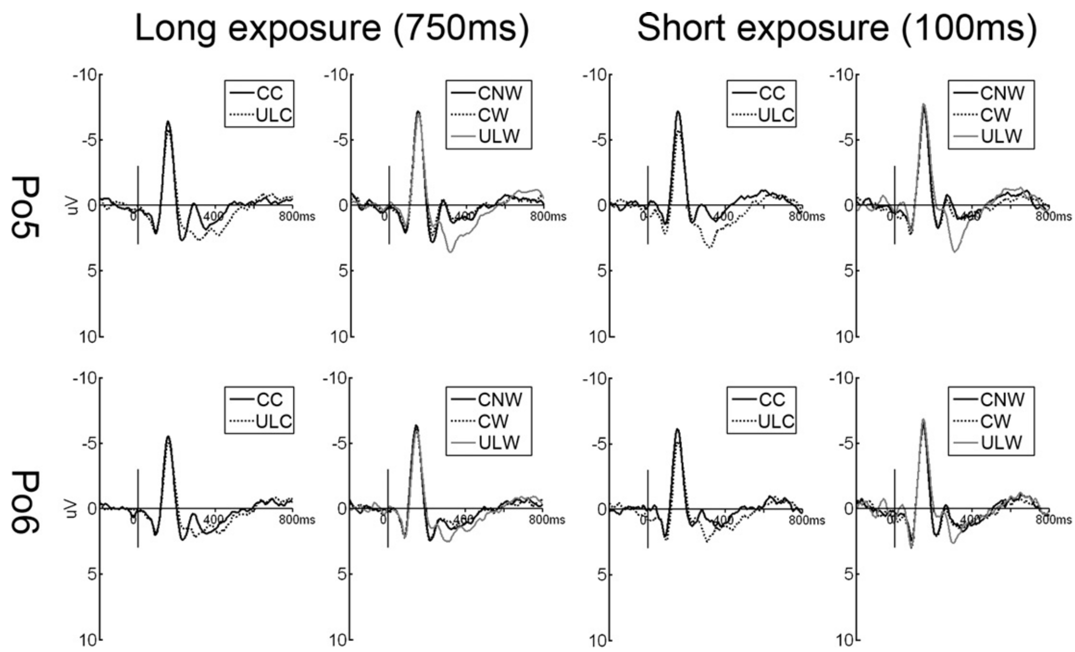

Fig. 3. ERPs for logographic writings. Grand averaged ERPs ($n=13$) recorded at the left (PO5) and right (PO6) electrodes are plotted as a function of stimulus type and presentation duration.

To investigate the significant interactions, we did further simple effect analyses to examine the language experience effects separately by their significant moderators (stimulus length and writing system). This analysis revealed a significantly stronger N1 response to English letters than to unfamiliar alphabetic letters [$F(1,12)=20.190$, $p=.001$], and to Chinese characters than to unfamiliar logographic characters [$F(1,12)=11.315$, $p=.006$]. However, there were no language experience effects for either logographic or alphabetic words (both F values $<.36$). Direct comparisons revealed that the language experience effect was stronger for alphabetic letters [$t(12)=3.42$, $p=.005$] and logographic characters [$t(12)=2.78$, $p=.017$] than for their word versions. Furthermore, the language experience effect was stronger for alphabetic letters than for logographic characters [$t(12)=3.12$, $p=.009$], but there were no significant differences between alphabetic words and logographic words [$t(12)=-.46$, $p=.653$], reflecting the language experience by stimulus length by writing system three-way interaction. Although the overall interaction between language experience and presenta-

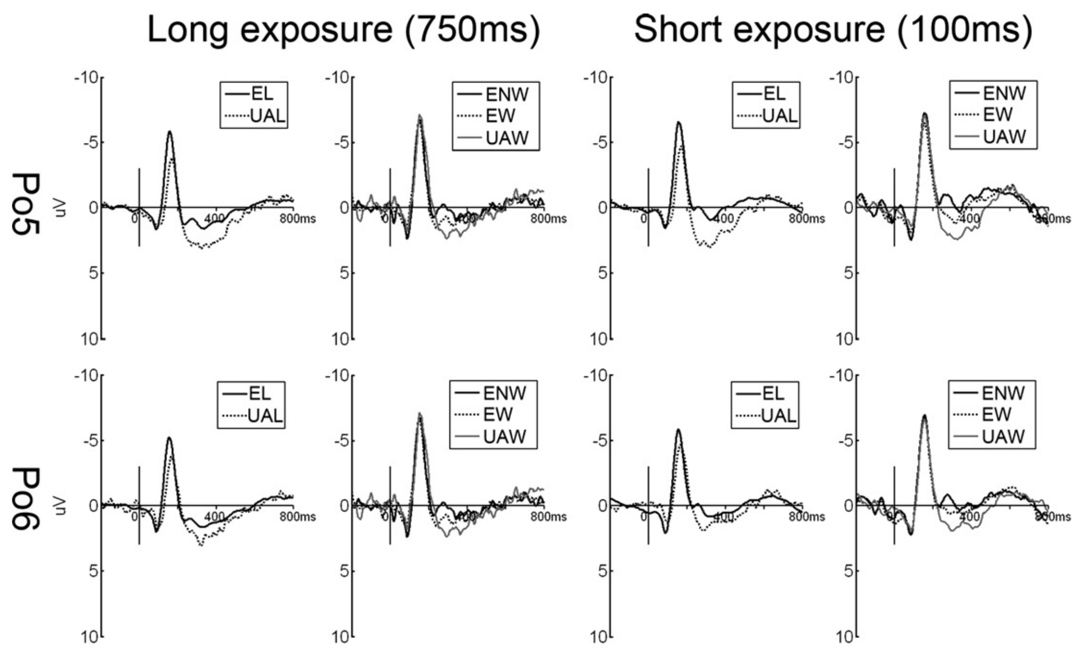

Fig. 4. ERPs for alphabetic writings. Grand averaged ERPs ($n=13$) recorded at the left (PO5) and right (PO6) electrodes are plotted as a function of stimulus type and presentation duration.

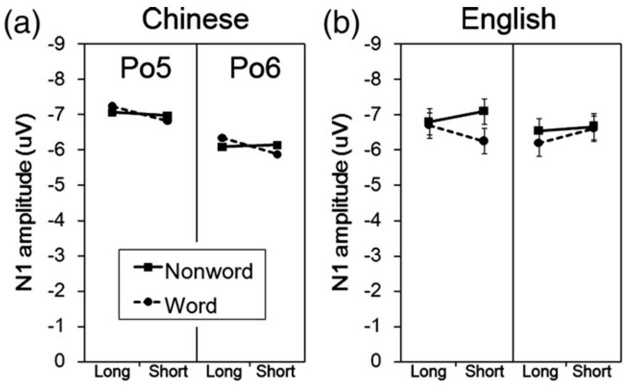

Fig. 5. The absence of lexicality effects. Averages of the N1 response in PO5 (left), PO6 (right) over a time window of ±10 ms around the peak of each condition are plotted as a function of stimulus type and presentation duration. Error bars represent within-subject errors.

tion duration was not significant, the language experience effect for logographic characters appeared larger under the short duration than under the long duration condition. This was confirmed by the marginally significant language experience by duration interaction [$F(1,12)=4.200$, $p=.063$]. Further analysis revealed that the language experience effect was significant only under the short duration condition [$F(1,12)=16.890$, $p=.001$], not under the long duration condition [$F(1,12)=2.830$, $p=.120$].

The effect of stimulus length

Because a comparison between alphabetic letters and alphabetical words may be confounded by the different number of repetitions of the same stimuli (letters, but not words, were repeated three times due to the small number of letters), we limited our analysis of the effect of stimulus length to the comparison between logographic words and characters. Four-way ANOVA revealed a significant stimulus length effect [$F(1,12)=18.481$, $p=.001$], and a length by language experience interaction [$F(1,12)=7.74$, $p=.017$], reflecting a much stronger length effect for the unfamiliar logographic writing than for Chinese. Simple effect analysis revealed a significant length effect for the unfamiliar logographic writing [$F(1,12)=21.045$, $p=.001$], but only a marginally significant effect for Chinese [$F(1,12)=3.80$, $p=.075$].

The effect of writing systems

Also to avoid the repetition effect for alphabetic letters, we examined the effect of writing systems by comparing only logographic words and alphabetic words. Four-way ANOVA revealed no significant main effects or interactions (all p values >.15).

Discussion

To achieve a better understanding of the relation between N1 response and language experience and to elucidate possible mechanisms of N1 response, the present ERP study examined the effect of language experience on the amplitude of the early N1 response and how it is modulated by writing system, stimulus length, and presentation duration. In this section, we will first discuss the language experience effect, as revealed by the comparisons between familiar and unfamiliar writings as well as the lexicality effect. We will then discuss the characteristics of the N1 response. Finally, we will try to integrate these data to postulate possible mechanisms of the N1 response during visual word recognition and suggest questions for future research.

How does language experience change the N1 response?

The effect of language experience on the N1 response has generally been examined by comparing stimuli with different lexical status, like non-words or consonant strings, pseudowords, and words, or by comparing language with nonlinguistic materials, including false fonts, symbols, and foreign writings. Whereas the former approach can examine the effects of higher-level factors (e.g., orthography, phonology, and semantics) on word recognition, the latter can examine the combined effects of both higher-level factors and lower-level factors (e.g., letter identification).

The present study examined the lexicality effect by comparing words with non-words (Chinese language) as well as words with consonant strings (English language). The absence of the lexicality effect is consistent with many previous studies (Bentin et al., 1999; Cohen et al., 2000; Khateb et al., 2002; Maurer et al., 2005b; Nobre et al., 1994; Proverbio et al., 2004; Schendan et al., 1998; Shirahama et al., 2004; Wydell et al., 2003). Nevertheless, a significant N1 difference had been revealed in previous studies between orthographic and non-orthographic stimuli (Compton et al., 1991; Dehaene, 1995; McCandliss et al., 1997), words and pseudowords (Hauk et al., 2006; McCandliss et al., 1997), verbs and nouns (Koenig and Lehmann, 1996), words belonging to dif-

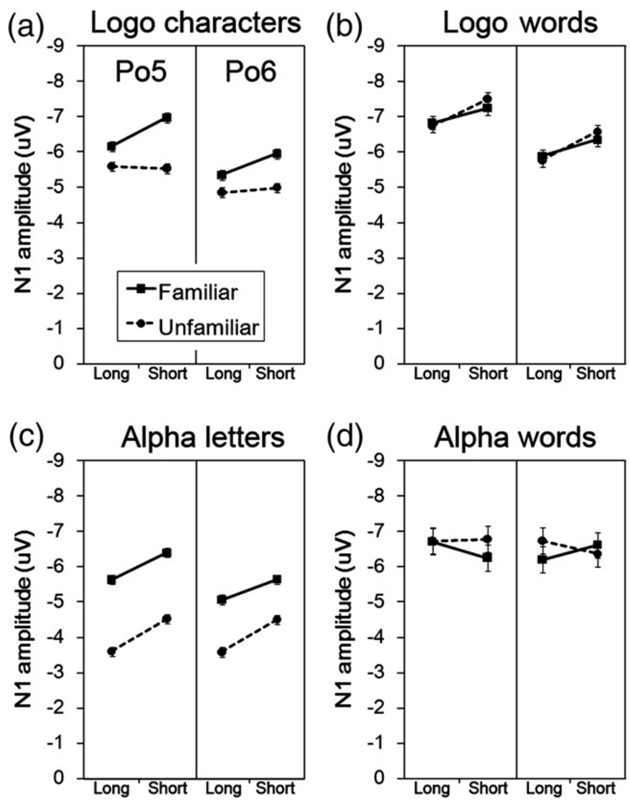

Fig. 6. Language experience effects were modulated by stimulus length and presentation duration. Please refer to the caption of Fig. 5 for more details. Long: long duration; Short: short duration. Logo: Logographic; Alpha: Alphabetic.

ferent semantic classes (Koenig and Lehmann, 1996; Pulvermuller et al., 2001; Skrandies, 1998, 2004; Skrandies and Chiu, 2003), and words with different levels of semantic coherence (Hauk et al., 2006). These results suggest that linguistic processes can affect the early N1 response, but whether or not this leads to a significant lexicality effect depends on many factors. We will return to this issue in a later section.

We also examined the differences between familiar and unfamiliar writings. We found a complex pattern of N1 sensitivity due to the modulation of orthography and stimulus length. A stronger N1 response to familiar writings than to unfamiliar writings was significant for alphabetic letters, but not for alphabetic and logographic words. Further, the language experience was bigger for alphabetic letters and logographic characters. We also found a marginally significant moderating effect of presentation duration. That is, the difference between Chinese characters and unfamiliar logographic characters was significant only under the short presentation duration, but not under the long presentation duration. These results suggest that N1 might not reliably differentiate familiar and unfamiliar writings, and it is significantly modulated by writing system and visual complexity (i.e., stimulus length).

Our results (especially those from the comparisons between familiar and unfamiliar alphabetic words) should be discussed in the context of the findings from previous research comparing language with symbol strings and false fonts. Most of previous studies that used symbol strings (e.g., familiar simple geometric shapes such as squares, rectangles, and diamond shapes) have found stronger activations to words than to simple symbol strings (Bentin et al., 1999; Brem et al., 2005; Maurer et al., 2005a,b; Tarkiainen et al., 2002, 1999). On the other hand, consistent with our results, studies using visually matched false fonts showed no robust differences between language and false fonts (Eulitz et al., 2000; Schendan et al., 1998). One interpretation of these results is that the N1 differences reflect ”coarse” specialization of visual word processing due to visual expertise with writings, letter strings, false fonts, but not symbol strings. Alternatively, however, the differences in the N1 effect could be attributed to several other factors, including differences in experimental tasks (one-back comparison vs. passive viewing and feature detection), systematicness (symbols vs. pseudo/real writings), complexity (simple vs. visually matched), and familiarity (familiar vs. unfamiliar) of the visual stimuli. As will be discussed below, some of these factors might have a significant effect on the N1 response.

N1 response is modulated by writing system and visual complexity

First, we found that writing system can modulate the language experience effect. Although there was a difference between English letters and unfamiliar alphabetic letters, the difference between Chinese characters and unfamiliar logographic characters was more subtle and less reliable. The absence of difference between familiar and unfamiliar logographic characters under the 750 ms presentation duration is consistent with previous fMRI results (Xue et al., 2006). This suggests that unfamiliar logographic writings might elicit an N1 response comparable to or even stronger than that elicited by familiar logographic writings. Consistently, a previous ERP study revealed a stronger N1 for Asiatic characters than for letters even for subjects who had no experience with Asiatic characters (Pernet et al., 2003). Stronger fusiform activation has also been found for Chinese than for English stimuli even when the subjects were English speakers and had only limited exposure to the Chinese language (Liu et al., 2007). These results seem to be inconsistent with those of Wong et al. (2005), who found a stronger N1 response to Roman letters than to Chinese characters among English speakers. However, in their study, only eight simple Chinese characters (matched with Roman letters in visual complexity) were used and repeated many times. Their results might be confounded by different priming effects for familiar and unfamiliar writings. Furthermore, the writing-system effect we found cannot be attributed to a transfer between Chinese and Korean (due to their visual similarity) because it has been found that English speakers who had no experience with any logographic writings also showed similar middle fusiform activation between English and Korean Hangul (Xue and Polrack, 2007). Nevertheless, further studies need to examine this issue by studying participants with no experience of any logographic language (Xue and Polrack, 2007), or by comparing the N1 response to an unfamiliar logographic writing (e.g., Korean Hangul) by subjects with different language backgrounds (e.g., Chinese vs. English readers).

The present study also revealed a significant effect of stimulus length on the N1 response. A stronger N1 response was found with long stimuli than with short stimuli, which replicates previous findings (Wong et al., 2005; Wydell et al., 2003). A further examination of our data suggested that stimulus length (or visual complexity in general) had a stronger effect on unfamiliar writings than on familiar writings. These results are consistent with behavioral data indicating a decreased word length/complexity effect for familiar writings. This result has important implications for our understanding of the mechanisms of the N1 response, which will be discussed below.

So far, relatively few studies have examined the effect of presentation duration on the N1 response. Although the present study did not reveal a consistent presentation duration effect, the significant interaction between presentation duration and language experience is very important. This pattern is consistent with our previous fMRI data that showed no differences between familiar and unfamiliar writings under a long presentation duration condition (Xue et al., 2006). One reason for this interaction might be that under the short presentation duration condition, familiar writings attracted more attention than did unfamiliar writings, which in turn increased the synchrony of the LFPs (Fries et al., 2001) and the ERP response (see Engel et al., 2001 for a review). In contrast, under the long-duration presentation condition, the differences between familiar and unfamiliar writings might have been greatly reduced. Consistent with this speculation, a larger N1 response under the short duration than under the long duration condition was found only for familiar writings [$F(1,12)=3.39$, $p=.09$], but not for unfamiliar writings ($p=.94$).

What can N1 tell us about visual word recognition?

So what can the above results tell us about the mechanisms of the N1 response to visual word processing? There is a long-standing assumption about the visual expertise effect in visual word form processing. However, this assumption has not been supported by compelling evidence (see Xue et al., 2006 for a discussion on behavioral and fMRI evidence). In the following paragraphs, we will argue that, based on the above characteristics of the N1 response, the connection between the enhanced N1 amplitude and visual expertise is questionable.

One salient finding of the present study was that the effect of language experience was modulated by stimulus length. Further analysis suggested that stimulus length enhanced the N1 response, more so for unfamiliar writings than for familiar writings. This result is inconsistent with the visual-expertise-induced sensitivity hypothesis, which would expect only a main effect of language experience, not its interaction with stimulus length. Moreover, we found that language experience reduced the visual complexity effect, which again is not consistent with this hypothesis. We think our results need to be explained by multiple processes involved in visual word processing. Some of those processes may counteract one another. For example, functional imaging studies have shown that visual familiarity or visual expertise decreases the neural response (Xue et al., 2006; Xue and Polrack, 2007), whereas linguistic components such as phonology and semantics associated with the visual words increase the neural response (Xue et al., 2006). Consistently, preliminary ERP data have shown that visually unfamiliar text (e.g., mirror text) elicited stronger N1 responses than did visually familiar text (e.g., normal text), suggesting that increased visual familiarity reduces the N1 response (Proverbio et al., 2007).

The top–down modulation of the early N1 response has been supported by many observations (see Introduction and above Discussion). Particularly, it is well known from previous literature that linguistic, task-related, and attentional factors can have a substantial effect on the amplitude of N1 (Luck et al., 2000). Cumulating evidence suggests that the speed of processing and information flow through the visual system and the time-window for possible top–down modulation is much faster than it was assumed. For example, the first afferent volley could reach the frontal lobe 80 ms post-stimulus (Foxe and Simpson, 2002; Thorpe et al., 1996). It has been shown that the ERP components might be indicative of recurrent feedback-driven processes rather than the first information sweep through the system (Buchner et al., 1997; also see Sereno and Rayner, 2003 for a review).

The above hypothesis can explain not only the results observed in this study but also those of previous studies. That is, for visually complex stimuli (e.g., words vis-à-vis letters), the N1 component is mainly modulated by visual complexity, and the neural decreases due to increased visual familiarity or visual expertise will outweigh the neural increases caused by the acquisition of linguistic components (e.g., sounds and meanings), resulting in an overall decrease in the N1 response. Whereas for visually simple stimuli (i.e., single letters), the effect of visual expertise would be small and thus could be outweighed by the effect of linguistic components, resulting in an overall increase in the N1 response. This idea fits well with the significant interactions found between language experience and visual complexity—that is, a smaller stimulus length effect for familiar writings than for unfamiliar writings and the absence of language sensitivity for visually complex stimuli, like alphabetical and logographic words.

Our hypothesis might also explain the absence of the lexicality effect in this study. The lexicality effect (comparisons between logographic words and non-words and between alphabetic words and consonant strings) usually reflects an integrated influence of visual familiarity, orthography, phonology, and semantics (Xue et al., 2006). Because these factors have differential effects on the neural response to visual words, as shown by previous fMRI data on fusiform activation, they might counteract one another, resulting in an absence of the lexicality effect under certain circumstances. For example, different task requirements might have differentially emphasized visual forms, phonological, or semantic processing, resulting in discrepant findings (see Table 1).

Although our speculation provides a potentially promising way to resolve the discrepancies in existing research, further studies are necessary to directly examine this hypothesis. Particularly, artificial language training paradigms that can separate these effects will be very helpful (Xue et al., 2006). Furthermore, our hypothesis also points to the importance of examining factors such as stimulus presentation duration (Martin et al., 2006) and task requirements. Finally, the combination of ERP and fMRI techniques will also be useful for characterizing the neural responses associated with the early stage (spatially and temporally) of visual word recognition, as well as to provide important information on the role of bottom–up physical factors and top–down linguistic factors in this process.

Conclusion

Reading represents an important type of visual object processing. Although many studies have emphasized the role of visual expertise in shaping the cognitive and neural changes in the early stage of visual word recognition, its exact effects on neural response as indexed by the N1 response has been controversial. Our study suggests that there are a number of factors aside from visual expertise, such as writing system and visual complexity, could affect the N1 response. Moreover, emerging evidence has suggested that linguistic factors could affect the processes that occur in the early stage of the neural circuitry, such as the primary visual system, and within 150–200 ms of the stimulus presentation. Thus, a careful examination and separation of the different effects of visual and linguistic factors on the neural response will help us to obtain a better understanding of how language experience affects reading.

Acknowledgments

We wish to thank Jin Li, Sibin Qiao, Qinghua He for their help in data collection and analysis, and Tian Li, Libo Zhao and Feng Xue for their help in material preparation. We also want to thank Jared Lessard for his helpful comments on an earlier draft of the manuscript. This study was supported by National Pan Deng project (95-special-09) and the 111 project.

References

Assadollahi, R., Pulvermuller, F., 2001. Neuromagnetic evidence for early access to cognitive representations. NeuroReport 12, 207–213.

Barber, H.A., Kutas, M., 2007. Interplay between computational models and cognitive electrophysiology in visual word recognition. Brain Res. Brain Res. Rev. 53, 98–123.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M.H., Echallier, J.F., Pernier, J., 1999. ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. J. Cogn. Neurosci. 11, 235–260.

Brem, S., Lang-Dullenkopf, A., Maurer, U., Halder, P., Bucher, K., Brandeis, D., 2005. Neurophysiological signs of rapidly emerging visual expertise for symbol strings. NeuroReport 16, 45–48.

Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., et al., 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. NeuroImage 29, 822–837.

Buchner, H., Gobbele, R., Wagner, M., Fuchs, M., Waberski, T.D., Beckmann, R., 1997. Fast visual evoked potential input into human area V5. NeuroReport 8, 2419–2422.

Burgund, E.D., Schlaggar, B.L., Petersen, S.E., 2006. Development of letter-specific processing: the effect of reading ability. Acta Psychol. (Amst) 122, 99–108.

Chen, Y.P., Allport, D.A., Marshall, J.C., 1996. What are the functional orthographic units in Chinese word recognition: the stroke or the stroke pattern. Q. J. Exp. Psychol. 49, 1024–1043.

Chen, C., Xue, G., Dong, Q., Jin, Z., Li, T., Xue, F., et al., 2007. Sex determines the neurofunctional predictors of visual word learning. Neuropsychologia 45, 741–747.

Cohen, L., Dehaene, S., 2004. Specialization within the ventral stream: the case for the visual word form area. NeuroImage 22, 466–476.

Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., Henaff, M.A., et al., 2000. The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. Brain 123 (Pt 2), 291–307.

Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., Dehaene, S., 2002. Language-specific tuning of visual cortex? Functional properties of the visual word form area. Brain 125, 1054–1069.

Compton, P.E., Grossenbacher, P., Posner, M.I., Tucker, D.M., 1991. A cognitive–anatomical approach to attention in lexical access. J. Cogn. Neurosci.. Special Issue: The University of Oregon Center for Cognitive Neuroscience of Attention 3, 304–312.

Dehaene, S., 1995. Electrophysiological evidence for category-specific word processing in the normal human brain. NeuroReport 6, 2153–2157.

Engel, A.K., Fries, P., Singer, W., 2001. Dynamic predictions: oscillations and synchrony in top–down processing. Nat. Rev., Neurosci. 2, 704–716.

Eulitz, C., Eulitz, H., Maess, B., Cohen, R., Pantev, C., Elbert, T., 2000. Magnetic brain activity evoked and induced by visually presented words and nonverbal stimuli. Psychophysiology 37, 447–455.

Foxe, J.J., Simpson, G.V., 2002. Flow of activation from V1 to frontal cortex in humans. A framework for defining "early" visual processing. Exp. Brain Res. 142, 139–150.

Fries, P., Reynolds, J.H., Rorie, A.E., Desimone, R., 2001. Modulation of oscillatory neuronal synchronization by selective visual attention. Science 291, 1560–1563.

Gauthier, I., Curran, T., Curby, K.M., Collins, D., 2003. Perceptual interference supports a non-modular account of face processing. Nat. Neurosci. 6, 428–432.

Gros, H., Doyon, B., Rioual, K., Celsis, P., 2002. Automatic grapheme processing in the left occipitotemporal cortex. NeuroReport 13, 1021–1024.

Hauk, O., Pulvermuller, F., 2004. Effects of word length and frequency on the human event-related potential. Clin. Neurophysiol. 115, 1090–1103.

Hauk, O., Davis, M.H., Ford, M., Pulvermuller, F., Marslen-Wilson, W.D., 2006. The time course of visual word recognition as revealed by linear regression analysis of ERP data. NeuroImage 30, 1383–1400.

Huang, K., Itoh, K., Suwazono, S., Nakada, T., 2004. Electrophysiological correlates of grapheme–phoneme conversion. Neurosci. Lett. 366, 254–258.

Indefrey, P., Kleinschmidt, A., Merboldt, K.D., Kruger, G., Brown, C., Hagoort, P., et al., 1997. Equivalent responses to lexical and nonlexical visual stimuli in occipital cortex: a functional magnetic resonance imaging study. NeuroImage 5, 78–81.

Khateb, A., Pegna, A.J., Michel, C.M., Landis, T., Annoni, J.M., 2002. Dynamics of brain activation during an explicit word and image recognition task: an electrophysiological study. Brain Topogr. 14, 197–213.

Koenig, T., Lehmann, D., 1996. Microstates in language-related brain potential maps show noun–verb differences. Brain Lang. 53, 169–182.

Lehmann, D., Skrandies, W., 1980. Reference-free identification of components of checkerboard-evoked multichannel potential fields. Electroencephalogr. Clin. Neurophysiol. 48, 609–621.

Liu, Y., Perfetti, C.A., 2003. The time course of brain activity in reading English and Chinese: an ERP study of Chinese bilinguals. Hum. Brain Mapp. 18, 167–175.

Liu, Y., Dunlap, S., Fiez, J., Perfetti, C., 2007. Evidence for neural accommodation to a writing system following learning. Hum. Brain Mapp. 28, 1223–1234.

Loftus, G., Masson, M., 1994. Using confidence intervals in within-subject designs. Psychon. Bull. Rev. 1, 476–490.

Luck, S.J., Woodman, G.F., Vogel, E.K., 2000. Event-related potential studies of attention. Trends Cogn. Sci. 4, 432–440.

Martin, C.D., Nazir, T., Thierry, G., Paulignan, Y., Demonet, J.F., 2006. Perceptual and lexical effects in letter identification: an event-related potential study of the word superiority effect. Brain Res. 1098, 153–160.

Maurer, U., Brandeis, D., McCandliss, B.D., 2005a. Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. Behav. Brain Funct. 1, 13.

Maurer, U., Brem, S., Bucher, K., Brandeis, D., 2005b. Emerging neurophysiological specialization for letter strings. J. Cogn. Neurosci. 17, 1532–1552.

Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., et al., 2006. Coarse neural tuning for print peaks when children learn to read. NeuroImage 33, 749–758.

McCandliss, B.D., Posner, M.I., Givon, T., 1997. Brain plasticity in learning visual words. Cogn. Psychol. 33, 88–110.

McCandliss, B.D., Cohen, L., Dehaene, S., 2003. The visual word form area: expertise for reading in the fusiform gyrus. Trends Cogn. Sci. 7, 293–299.

Moscoso del Prado Martin, F., Hauk, O., Pulvermuller, F., 2006. Category specificity in the processing of color-related and form-related words: an ERP study. NeuroImage 29, 29–37.

Nobre, A.C., Allison, T., McCarthy, G., 1994. Word recognition in the human inferior temporal lobe. Nature 372, 260–263.

Peissig, J.J., Singer, J., Kawasaki, K., Sheinberg, D.L., 2007. Effects of long-term object familiarity on event-related potentials in the monkey. Cereb. Cortex. 17, 1323–1334.

Pelli, D.G., Farell, B., Moore, D.C., 2003. The remarkable inefficiency of word recognition. Nature 423, 752–756.

Perfetti, C.A., Hogaboam, T., 1975. Relationship between single work decoding and reading comprehension skill. J. Educ. Psychol. 67, 461–469.

Perfetti, C.A., Wlotko, E.W., Hart, L.A., 2005. Word learning and individual differences in word learning reflected in event-related potentials. J. Exp. Psychol. Learn. Mem. Cogn. 31, 1281–1292.

Pernet, C., Basan, S., Doyon, B., Cardebat, D., Demonet, J.F., Celsis, P., 2003. Neural timing of visual implicit categorization. Brain Res. Cogn. Brain Res. 17, 327–338.

Polk, T.A., Farah, M.J., 2002. Functional MRI evidence for an abstract, not perceptual, word-form area. J. Exp. Psychol. Gen. 131, 65–72.

Price, C.J., Devlin, J.T., 2003. The myth of the visual word form area. NeuroImage 19, 473–481.

Price, C.J., Wise, R.J., Watson, J.D., Patterson, K., Howard, D., Frackowiak, R.S., 1994. Brain activity during reading. The effects of exposure duration and task. Brain 117 (Pt 6), 1255–1269.

Price, C.J., Moore, C.J., Frackowiak, R.S., 1996. The effect of varying stimulus rate and duration on brain activity during reading. NeuroImage 3, 40–52.

Proverbio, A.M., Vecchi, L., Zani, A., 2004. From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. J. Cogn. Neurosci. 16, 301–317.

Proverbio, A., Zotto, M., Zani, A., 2006. Greek language processing in naive and skilled readers: functional properties of the VWFA investigated with ERPs. Cogn. Neuropsychol. 23, 355–375.

Proverbio, A.M., Wiedemann, F., Adorni, R., Rossi, V., Del Zotto, M., Zani, A., 2007. Dissociating object familiarity from linguistic properties in mirror word reading. Behav. Brain Funct. 3, 43.

Pulvermuller, F., Assadollahi, R., Elbert, T., 2001. Neuromagnetic evidence for early semantic access in word recognition. Eur. J. Neurosci. 13, 201–205.

Reicher, G.M., 1969. Perceptual recognition as a function of meaningfulness of stimulus material. J. Exp. Psychol. 81, 274–280.

Rossion, B., Gauthier, I., Goffaux, V., Tarr, M.J., Crommelinck, M., 2002. Expertise training with novel objects leads to left-lateralized facelike electrophysiological responses. Psychol. Sci. 13, 250–257.

Rossion, B., Joyce, C.A., Cottrell, G.W., Tarr, M.J., 2003. Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. NeuroImage 20, 1609–1624.

Schendan, H.E., Ganis, G., Kutas, M., 1998. Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. Psychophysiology 35, 240–251.

Scott, L.S., Tanaka, J.W., Sheinberg, D.L., Curran, T., 2006. A reevaluation of the electrophysiological correlates of expert object processing. J. Cogn. Neurosci. 18, 1453–1465.

Sereno, S.C., Rayner, K., 2003. Measuring word recognition in reading: eye movements and event-related potentials. Trends Cogn. Sci. 7, 489–493.

Shirahama, Y., Ohta, K., Takashima, A., Matsushima, E., Okubo, Y., 2004. Magnetic brain activity elicited by visually presented symbols and Japanese characters. NeuroReport 15, 771–775.

Skrandies, W., 1998. Evoked potential correlates of semantic meaning—A brain mapping study. Brain Res. Cogn. Brain Res. 6, 173–183.

Skrandies, W., 2004. Brain mapping of evoked potential correlates of semantic meaning—cross-cultural studies. Int. Congr. Ser. 1270, 61–66.

Skrandies, W., Chiu, M.J., 2003. Dimensions of affective semantic meaning—behavioral and evoked potential correlates in Chinese subjects. Neurosci. Lett. 341, 45–48.

Tanaka, J.W., Curran, T., 2001. A neural basis for expert object recognition. Psychol. Sci. 12, 43–47.

Tarkiainen, A., Helenius, P., Hansen, P.C., Cornelissen, P.L., Salmelin, R., 1999. Dynamics of letter string perception in the human occipitotemporal cortex. Brain 122 (Pt 11), 2119–2132.

Tarkiainen, A., Cornelissen, P.L., Salmelin, R., 2002. Dynamics of visual feature analysis and object-level processing in face versus letter-string perception. Brain 125, 1125–1136.

Thorpe, S., Fize, D., Marlot, C., 1996. Speed of processing in the human visual system. Nature 381, 520–522.

Wang, H., Chang, R.B., 1985. Modern Chinese Frequency Dictionary. Beijing Language University Press, Beijing.

Weekes, B.S., 1997. Differential effects of number of letters on word and nonword naming latency. Q. J. Exp. Psychol.: Section A 50, 439–456.

Wong, A.C., Gauthier, I., Woroch, B., DeBuse, C., Curran, T., 2005. An early electrophysiological response associated with expertise in letter perception. Cogn. Affect Behav. Neurosci. 5, 306–318.

Wydell, T.N., Vuorinen, T., Helenius, P., Salmelin, R., 2003. Neural correlates of letter-string length and lexicality during reading in a regular orthography. J. Cogn. Neurosci. 15, 1052–1062.

Xue, G., Poldrack, R.A., 2007. The neural substrates of visual perceptual learning of word: implications for the visual word form area hypothesis. J. Cogn. Neurosci. 19, 1643–1655.

Xue, G., Dong, Q., Chen, K., Jin, Z., Chen, C., Zeng, Y., et al., 2005. Cerebral asymmetry in children when reading Chinese characters. Brain Res. Cogn. Brain Res. 24, 206–214.

Xue, G., Chen, C., Jin, Z., Dong, Q., 2006. Language experience shapes fusiform activation when processing a logographic artificial language: an fMRI training study. NeuroImage 31, 1315–1326.