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Research report

Processing emotional words in two languages with one brain: ERP and fMRI evidence from Chinese–English bilinguals

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ABSTRACT

Emotional words in a bilingual's second language (L2) seem to have less emotional impact compared to emotional words in the first language (L1). The present study examined the neural mechanisms of emotional word processing in Chinese–English bilinguals' two languages by using both event-related potentials (ERPs) and functional magnetic resonance imaging (fMRI). Behavioral results show a robust positive word processing advantage in L1 such that responses to positive words were faster and more accurate compared to responses to neutral words and negative words. In L2, emotional words only received higher accuracies than neutral words. In ERPs, positive words elicited a larger early posterior negativity and a smaller late positive component than neutral words in L1, while a trend of reduced N400 component was found for positive words compared to neutral words in L2. In fMRI, reduced activation was found for L1 emotional words in both the left middle occipital gyrus and the left cerebellum whereas increased activation in the left cerebellum was found for L2 emotional words. Altogether, these results suggest that emotional word processing advantage in L1 relies on rapid and automatic attention capture while facilitated semantic retrieval might help processing emotional words in L2.

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1. Introduction

Our daily lives are filled with a variety of emotional experiences, such as happiness, anger, sadness, or fear. Most people are able to freely express their feelings in their native language (L1). However, as second language (L2) speakers, bilinguals frequently report experiencing weaker emotional activation in their L2 compared to their L1 (Pavlenko, 1998). Therefore, L1 is considered emotionally close, whereas L2 is emotionally distant (Bond & Lai, 1986).

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Emotional words play an important role in expressing feelings. The emotional connotation of these words is the key feature that distinguishes them from neutral words (Altarriba, Bauer, & Benvenuto, 1999). Previous studies have used recall tasks to investigate whether bilinguals' weaker emotional experience in L2 is due to different processing mechanisms for emotional words in L2 and in L1. Several studies have found that bilinguals recall more emotional words, of which most were positive, in L1, while there was no such recall advantage for emotional words in L2 (e.g., Anooshian & Hertel, 1994). However, other studies have revealed that bilinguals show better memory for emotional words compared to neutral words both in L1 and L2 (Ayçiçeği & Harris, 2004; Ferré, García, Fraga, Sánchez-Casas, & Molero, 2010), an effect that was not influenced by age of acquisition, context of acquisition, or language similarity (Ferré et al., 2010). Behavioral studies using the emotional Stroop paradigm have also found comparable effects of emotion in bilinguals' L1 and L2 such that negative words were responded to significantly slower than neutral words (Eilola, Havelka, & Sharma, 2007; Sutton, Altarriba, Gianico, & Basnight-Brown, 2007).

Skin conductance response (SCR), a sensitive measure of autonomous arousal (Harris, 2004), has also been used in studies of bilingual emotional word processing. A series of studies comparing late bilinguals and early bilinguals residing in an L1 or L2 environment, showed that late bilinguals had a stronger SCR to emotional words (mainly taboo words and reprimands) in L1 compared to L2, regardless of the language environment they were immersed in (Eilola & Havelka, 2011; Harris, Ayçiçeği & Gleason, 2003). In contrast, early bilinguals showed no differences in SCR to emotional words between L1 and L2 (Harris, 2004). Based on these findings, Harris proposed that only emotional words acquired in emotional contexts could elicit sufficient emotional activation. Accordingly, emotional words acquired outside of an emotional context (e.g., classroom instruction), are unable to evoke autonomous arousal. Therefore, the emotional activation to emotional words in L2 may be weaker than in L1 (Harris, Gleason, & Ayçiçeği, 2006).

In summary, previous behavioral and psychophysiological studies have shed light on emotional word processing in bilinguals' L1 and L2. The SCR studies have found that bilinguals have larger SCRs to extreme negative emotional words in L1 compared to L2, however, differences in processing common emotional words in two languages are still unclear. The reaction time studies revealed a similar pattern in emotional word processing in L1 and L2. This could be due to the fact that reaction time only reflects an aggregate effect of processing, but is unable to reveal differences that might occur at intermediate stages of processing. Because emotional words in L2 are suggested to evoke less autonomous arousal, there would probably be differences in the time course of processing emotional words in bilinguals' two languages, and processing emotional words in L2 might require more neural activation related to emotional processing. Due to their high temporal and spatial resolution, respectively, event-related brain potentials (ERP) and functional magnetic resonance imaging (fMRI) would be helpful to shed light on these hypotheses. However, as will be reviewed below, previous ERP and fMRI studies have mainly investigated the neural mechanism of emotional word processing in monolinguals.

ERP studies on emotional word processing in L1 have found that both positive and negative words elicit a larger early posterior negativity (EPN), starting around 250–350 msec after stimulus onset compared to neutral words. The EPN has been suggested to reflect an automatic and rapid sub-process in which emotional words capture attention for later sustained processing (Herbert, Junghofer, & Kissler, 2008; Kissler, Herbert, Peyk, & Junghofer, 2007; Kissler, Herbert, Winkler, & Junghofer, 2009; Schacht & Sommer, 2009a; Scott, O'Donnell, Leuthold, & Sereno, 2009). This early emotion effect may reflect the activation of enhanced sensory resources in the visual cortex mediated by the emotional regulation system, including the amygdala and the cingulate cortex (Kissler et al., 2007). In the late time window of 450–700 msec, several studies have reported a larger late positive component (LPC) elicited by positive words compared to neutral words (Herbert, Kissler, Junghöfer, Peyk, & Rockstroh, 2006; Herbert et al., 2008; Kissler et al., 2009; Schacht & Sommer, 2009a, 2009b), or vice versa (Citron, 2011; Hinojosa, Carretié, Valcárcel, Méndez-Bértolo, & Pozo, 2009) while others have found that negative words induce a larger LPC compared to neutral words (Bayer, Sommer, & Schacht, 2010; Hofmann, Kuchinke, Tamm, Võ, & Jacobs, 2009; Schacht & Sommer, 2009a). This late positive component may reflect elaborate processing of the attended information (e.g., task demands) (Fischler & Bradley, 2006; Kissler, Assadollahi, & Herbert, 2006; Kissler et al., 2009; Schacht & Sommer, 2009b). A recent ERP study (Conrad, Recio, & Jacobs, 2011) investigated emotional word processing in highly-proficient German–Spanish and Spanish–German bilinguals using a lexical decision task. Results showed that the EPN and LPC were larger for emotional words than for neutral words in both L1 and L2, but the onset of EPN effect appeared in L2 were 50–100 msec later compared to it in L1, which suggests a general delayed L2 processing rather than a qualitatively different processing of emotional words across L1 and L2. This similar EPN effect, comparable on amplitude between L1 and L2 but delayed in L2, was also found in another study with late but proficient bilinguals (Opitz & Degner, 2012).

Previous fMRI studies on emotional word processing in L1 have shown that negative words, compared to neutral words, increased activation in the left amygdala (Hamann & Mao, 2002; Nakic, Smith, Busis, Vythilingam, & Blair, 2006), the right amygdala (Maddock, Garrett, & Buonocore, 2003; Nakic et al., 2006; Tabert et al., 2001;), the left cingulate cortex (George et al., 1994; Maddock & Buonocore, 1997; Whalen et al., 1998), the right cingulate cortex (Cato et al., 2004; Nakic et al., 2006), and the bilateral medial orbitofrontal cortex (Maddock et al., 2003). Positive words induced more activation in the left amygdala (Hamann & Mao, 2002; Herbert et al., 2009), the dorsal and ventral striatum including the caudate nucleus, the bilateral putamen, the left globus pallidus and the right nucleus accumbens (Hamann & Mao, 2002), the left orbitofrontal cortex (Kuchinke et al., 2005), the right orbitofrontal cortex (Maddock et al., 2003), the left dorsolateral prefrontal cortex (Maddock et al., 2003), and the bilateral cingulate cortex (Cato et al., 2004). Among these brain regions, the left and right amygdalae are usually associated with emotional information processing, especially negative emotion processing (Gläscher & Adolphs, 2003; Hamann & Mao, 2002; Phelps et al., 2001; Wright et al., 2001). The striatum is considered to be involved in the processing of positive or rewarding information (Canli, Desmond, Zhao, Glover, & Gabrieli, 1998; Elliott, Friston, & Dolan, 2000; Lane, Chua, & Dolan, 1997). The left orbitofrontal cortex and bilateral inferior frontal gyrus are related to emotional memory (Dolcos, LaBar, & Cabeza, 2004; Smith et al., 2004) and emotional evaluation (Cunningham et al., 2004). The posterior cingulate cortex is involved in the evaluation of emotional stimulus and context retrieval (Cato et al., 2004; Maddock et al., 2003). Furthermore, the anterior cingulate cortex, which is activated by the processing of negative and positive words, is usually related to attentional control (Cabeza & Nyberg, 2000) and emotional responses (Devinsky, Morrell, & Vogt, 1995). These findings suggest that relative to neutral words the processing of emotional connotation in words may activate additional brain regions related to emotion processing and emotional experience.

The goal of the present study was to use both ERPs and fMRI to examine 1) the time course of processing emotional words in L1 and L2, and 2) neural correlates contributing to processing emotional words in bilinguals' two languages. Based on previous behavioral and neural studies on bilingual emotional word processing, we predicted that reaction times would reveal a similar pattern in emotional word processing in L1 and L2. Meanwhile, we predicted a delayed EPN but a comparable LPC effect for emotional words in L2 compared to L1. As for the fMRI result, we predicted that processing L1 emotional words would activate more brain areas or have stronger activation in brain areas that related to emotional processing than L2 emotional words.

2. Experiments

2.1. *Experiment 1*

In the ERP experiment unbalanced Chinese–English bilinguals, who resided in their L1 environment and were dominant in their L1, were asked to perform a lexical decision task in L1 and L2. In order to rule out the possibility that lack of emotionality in L2 is due to the familiarity, word familiarity was also examined as a factor by frequently repeating a subset of the words in each language.

2.1.1. *Methods*

2.1.1.1. PARTICIPANTS. Twenty-four Chinese–English bilinguals participated in the ERP study. All participants were right-handed and had normal or corrected-to-normal vision. None of them reported any depression or mood disorders. Data from seven participants were excluded from the analysis. Of the seven, three completed the task without following the experimental instructions, and four were excluded because too few trials with correct responses remained after artifact rejection and exclusion of incorrect trials. The remaining seventeen Chinese–English bilinguals (8 females, $M = 22.47$, $SD = 1.84$) began learning English after the age of seven ($M = 11.36$, $SD = 2.07$) as assessed by a language history questionnaire. All participants gave informed consent prior to the experiment, which was approved by the Institutional Review Board of the Imaging Center for Brain Research of Beijing Normal University.

All participants took the CET-4 (College English Test, Band 4), a normalized English test taken by all Chinese college students, scored out of 710 total points ($M = 557.18$, $SD = 39.87$). The scores showed that these participants were relatively proficient English learners. Participants were also asked to self-rate their proficiency in reading, speaking, writing and comprehending Chinese and English on a 10-point scale (i.e., one being not proficient and 10 being highly proficient). The self-rating scores showed that the participants judged themselves more proficient in Chinese than in English (Chinese: $M = 8.01$, $SD = .97$; English: $M = 5.99$, $SD = 1.55$, $t_{16} = 6.44$, $p < .001$). As such, these participants were considered late and unbalanced bilinguals. Before the experiments, participants were asked to provide informed consent.

2.1.1.2. MATERIALS. The stimuli included 180 words of three different valence categories (60 positive words, 60 negative words, and 60 neutral words) and 180 pronounceable and orthographically legal pseudowords of both languages. English words were taken from previous studies (Eilola et al., 2007; Harris, 2004; Sutton et al., 2007) and from the Affective Norms for English Words (ANEW) database (Bradley & Lang, 1999), which were chosen on the basis of their emotional features. The English words were translated into Chinese by 10 undergraduate Chinese–English bilinguals. Another 19 Chinese–English bilinguals back-translated the Chinese words into English. Only words with consistent translations were included as experimental stimuli.

English words from the three different types were matched for word length ($F_{2,\ 179} = .59$, $p > .1$) and frequency ($F_{2,\ 179} = .01$, $p > .1$) based on the English Lexicon Project (Balota et al., 2007), whereas Chinese words were matched for visual complexity as indexed by stroke number ($F_{2,\ 179} = .33$, $p > .1$) and frequency ($F_{2,\ 179} = .01$, $p > .1$) (Wang, 1986).

Thirty-two Chinese–English bilinguals, not overlapping with the samples of the experiments, rated half of the Chinese words and the other half of the English words on emotional valence and arousal, respectively, on a 7-point scale (ranging from 1 to 7, with increasing values for stronger emotional resonance). Therefore, every participant rated a given word either in Chinese or English but not in both languages. The order of rating for Chinese and English words was counterbalanced across participants.

In Chinese, emotional arousal ratings for positive words ($M = 5.41$, $SD = .56$) and negative words ($M = 5.51$, $SD = .58$) were significantly higher than for neutral words ($M = 2.46$, $SD = .45$) ($ps < .001$) but did not differ from each other ($p > .1$). Ratings of emotional valence significantly increased from negative ($M = 1.94$, $SD = .45$) to neutral ($M = 4.24$, $SD = .40$) to positive words ($M = 6.11$, $SD = .34$) ($ps < .001$). In English, ratings of emotional arousal for positive words ($M = 5.40$, $SD = .52$) ($p < .001$) and negative words ($M = 5.41$, $SD = .57$) ($p < .001$) were significantly different from neutral words ($M = 2.65$, $SD = .38$), but not from each other ($p > .1$). Positive words were rated as more pleasant ($M = 6.02$, $SD = .45$) ($p < .001$) than neutral words ($M = 4.20$, $SD = .37$) and negative words as less pleasant ($M = 2.13$, $SD = .40$) ($p < .001$).

English pseudowords were selected from the database of the English Lexicon Project (Balota et al., 2007) with the criteria that each paired real word and pseudoword started with the same letter and were matched for length. Chinese pseudowords were created by randomly combining two Chinese characters that matched the stroke number of the real Chinese words.

In order to examine the effect of familiarity on emotional word processing, six positive, negative and neutral words in Chinese (matched for frequency and stroke number) and their English translation equivalents (also matched for length and frequency) were repeated nine times. Accordingly, eighteen pseudowords in each language were also presented nine times to balance the ratio of Yes/No judgments in lexical decisions. The remaining words and pseudowords in the two languages were presented once each. For the purpose of direct comparison across Experiment 1 and 2, we will only present results for the non-repeated condition. The results for the repeated condition will be summarized in the Supplementary material.

2.1.1.3. Procedure. Participants were tested individually in a quiet room. All of the stimuli were presented in black letters on a white background using the E-Prime software Version 2.0 (Psychology Software Tools Inc., Sharpsburg, USA) on a Dell PC. Chinese words were presented in Song font, size 24. English words were presented in lowercase Arial font, size 24. Chinese words and English words were randomly presented in two separate language blocks, and the order of blocks was counterbalanced across participants.

Each trial started with a fixation cross of 500 msec duration, followed by the word or pseudoword. Each word was presented for a maximum duration of 1 sec or disappeared immediately after the response. The inter-trial interval was 1.5 sec. Participants were instructed to judge whether the stimulus was a correct word as quickly and accurately as possible by pressing “Yes” or “No” keys marked on the keyboard with their index fingers. The assignment of participant's fingers to the “Yes” and “No” keys was counterbalanced. A practice block of 10 trials was provided before the experiment to ensure that participants understood the instructions. All participants were offered a break after every 81 trials.

After the main lexical decision task, participants were asked to complete an Operation Span task (Turner & Engle, 1989) in Chinese and the Simon task (Simon & Rudell, 1967). These tasks were used to measure individual differences in working memory span and attentional control, respectively. The entire experimental session lasted approximately 2.5 h.

2.1.1.4. Behavioral data. RTs for correct responses below 300 msec were excluded as absolute outliers, and RTs 2.5 standard deviations below or above each participant's mean value were excluded as relative outliers. The mean response times and accuracies were submitted to 2 (Language: L1 and L2) × 3 (Emotional valence: positive, negative, and neutral) repeated measures ANOVAs.

2.1.1.5. EEG recordings and analyses. The electroencephalogram (EEG) was recorded from 56 Ag/AgCl electrodes placed on the scalp according to the extended 10–20 system (Pivik et al., 1993) and was referenced to the left mastoid. Four additional electrodes were used for the vertical and horizontal electrooculogram. Electrode impedance was kept below 5 kΩ. All channels were amplified with a band pass of .05–70 Hz (50 Hz notch) and a sampling rate of 250 Hz. Offline, eye blinks were corrected by using the Gratton and Coles algorithm (Gratton, Coles, & Donchin, 1983) as implemented in the Brain Vision Analyzer. Continuous recordings were then segmented into epochs of 1,100 msec, starting 100 msec before stimulus onset, and were low-pass filtered at 30 Hz. Each epoch was referred to a 100 msec pre-stimulus baseline and was re-referenced to average reference. Finally, epochs containing artifacts were automatically discarded when the amplitudes exceeded -100 or $+100$ μV or when voltage steps >50 μV between adjacent sampling points occurred in any channel. After excluding trials with incorrect responses or artifacts, in L1 there remained 95%, 95% and 93% of trials for non-repeated positive, negative, and neutral words, respectively, and 97%, 97% and 94% for the corresponding repeated words. The corresponding numbers for non-repeated L2 words are 91%, 87%, and 85%, and for repeated L2 words they are 98%, 96%, and 95%. For all seventeen participants included in the final analysis, at least 40 trials per condition remained. Average ERPs were generated for each participant, electrode, and experimental condition.

Mean ERP amplitudes were calculated in consecutive 50 msec time windows between stimulus onset and 800 msec. As the EPN effect is most robust at the posterior sites (e.g., Conrad et al., 2011; Kissler et al., 2007; Opitz & Degner, 2012; Schacht & Sommer, 2009a), 10 posterior electrodes (P7/8, POz, PO3/4, PO7/8, Oz, and O1/2) were selected for this early emotional effect analysis. For the LPC effect, which is most robust at the centro-parietal sites, 9 centro-parietal electrodes (Pz, P1/2, P3/4, PO3/4, CPz, and POz) were selected. ANOVAs with Language (L1 and L2), Emotional Valence (positive, negative, and neutral), and Electrode (10 electrodes for the EPN effect and 9 electrodes for the LPC effect) as within subject factors were performed. Considering the possible delayed EPN effect in L2, we looked at every 50 msec time window from 200 to 500 msec. For the LPC effect, we analyzed time windows from 400 to 800 msec. When significant interactions between Language and Emotional Valence were found, post-hoc one-way ANOVAs (and pairwise comparisons) were performed within each language.

Since the emotion effect on ERPs was of particular interest in the current study, only the Emotional valence effect and interactions with Emotional valence will be reported here and all the significant main effects of language will be provided in the Supplementary material. All within-subject repeated measures ANOVAs will be reported with uncorrected degrees of freedom but Huynh-Feldt corrected p values. For post-hoc pairwise comparisons, Bonferroni correction was applied.

2.1.2. *Results*

2.1.2.1. Behavioral results. The behavioral results for Experiment 1 are shown in Table 1. In the RT analyses, the main effect of language was significant ($F_{1,\ 16} = 48.98$, $p < .001$, $\eta_p^2 = .75$), showing that participants responded faster to words in L1 than in L2. The effect of emotional valence also reached significance ($F_{2,\ 32} = 9.07$, $p < .001$, $\eta_p^2 = .36$). Overall, positive

Table 1 – Mean reaction times (RT) and accuracy rates (ACC) in the ERP experiment (standard deviation in parentheses).

	L1		L2	
	RT (msec)	ACC (%)	RT (msec)	ACC (%)
Positive	576 (63)	96.76 (3.09)	723 (84)	92.82 (4.92)
Negative	601 (61)	96.18 (3.56)	730 (80)	87.94 (5.57)
Neutral	601 (57)	94.41 (4.02)	725 (97)	87.47 (6.21)

words were responded to faster than both neutral ($p < .005$) and negative words ($p < .005$). The two-way interaction between language and emotional valence was significant ($F_{2, 32} = 3.67$, $p = .41$, $\eta_p^2 = .19$). Further comparisons revealed that the effect of emotional valence was only significant in L1 ($F_{2, 32} = 14.77$, $p < .001$, $\eta_p^2 = .48$), with faster responses to positive compared to neutral ($p < .005$) and negative words ($p < .001$). In contrast, the main effect of emotional valence was not significant in L2 ($F_{2, 32} < 1$).

In the accuracy analyses, the main effect of language was significant ($F_{1, 16} = 38.72$, $p < .001$, $\eta_p^2 = .71$), indicating that accuracy for words in L1 was higher than that in L2. The main effect of emotional valence was also significant ($F_{2, 32} = 18.47$, $p < .001$, $\eta_p^2 = .54$). Further comparison showed that the accuracy for positive words was higher than for neutral words ($p < .001$), and negative words ($p < .005$). Furthermore, the interaction of language and emotional valence was significant ($F_{2, 32} = 4.18$, $p = .03$, $\eta_p^2 = .21$). Further comparison revealed that in L1, the main effect of emotional valence was significant ($F_{2, 32} = 4.43$, $p = .02$, $\eta_p^2 = .22$), indicating that accuracy for positive words was higher than for neutral words ($p = .046$). In L2, the main effect of emotional valence was also significant ($F_{2, 32} = 13.18$, $p < .001$, $\eta_p^2 = .45$), indicating that accuracy for positive words was higher than for neutral words ($p < .005$), and negative words ($p < .005$).

2.1.2.2. ERP RESULTS. Figs. 1 and 2 show the ERP waveforms for each condition at selected electrode sites and topographical maps. As can be seen, all conditions evoked similar early components, such as P1 and N2. Visual inspection suggests that emotional words in L1 elicited larger negative-going waves than neutral words around the 250–400 msec time window at posterior electrode sites. This posterior negativity is accompanied by a frontal positivity and hence resembles the classical EPN. In addition, emotional words in L1 elicited smaller positive-going waves than neutral words starting at the time window of 500–800 msec at centro-parietal electrodes. In L2 word processing, neutral words seemed to elicit a reduced positivity compared to emotional words at the parietal sites during the 400–500 msec time window. All of these visual differentiations were confirmed by the statistical results.

In the time windows of 250–300 msec and 300–350 msec, the interaction between language and emotional valence was significant (250–300 msec: $F_{2, 32} = 7.62$, $p < .005$, $\eta_p^2 = .32$; 300–350 msec: $F_{2, 32} = 4.67$, $p = .02$, $\eta_p^2 = .23$). Post-hoc comparisons showed that the main effect of emotional valence was significant in L1 during both time windows (250–300 msec: $F_{2, 32} = 3.84$, $p = .03$, $\eta_p^2 = .19$; 300–350 msec: $F_{2, 32} = 4.15$, $p = .03$, $\eta_p^2 = .21$). Pairwise comparisons showed that the difference between the mean amplitudes for positive and neutral words in L1 was significant in the 250–300 msec time window ($p = .04$) and was marginally significant in the 300–350 msec time window ($p = .055$), indicating that positive words elicited a larger negativity at parieto-occipital sites (i.e., an enhanced EPN effect). In L2, the emotional valance main effect was marginally significant in the 250–300 msec time window ($F_{2, 32} = 3.03$, $p = .07$, $\eta_p^2 = .16$) but was not significant in the 300–350 time window ($F_{2, 32} < 1$). Although pairwise comparisons showed no difference between emotional and neutral words in L2 during 250–300 msec ($ps > .097$), the pattern of these emotional effects were opposite to those in L1, showing that emotional words elicited smaller negativities than neutral words did.

In the time window of 450–500 msec, the interaction between language and emotion (in the analysis for the LPC effect) was significant ($F_{2, 32} = 4.55$, $p = .02$, $\eta_p^2 = .22$). Post-hoc analysis showed that the emotional valence effect was not significant in L1 ($F_{2, 32} = 2.05$, $p = .15$, $\eta_p^2 = .11$) but marginally significant in L2 ($F_{2, 32} = 3.17$, $p = .059$, $\eta_p^2 = .17$). Post-hoc pairwise comparisons did not reveal any difference between emotional words and neutral words ($ps > .099$).

During the time windows of 500–550 msec and 550–600 msec, there was a significant interaction between language and emotional valence (500–550 msec: $F_{2, 32} = 3.81$, $p = .03$, $\eta_p^2 = .19$; 550–600 msec: $F_{2, 32} = 4.77$, $p = .02$, $\eta_p^2 = .23$). As in the early time window, the main effect of emotional valence was significant only in L1 (500–550 msec: $F_{2, 32} = 4.07$, $p = .03$, $\eta_p^2 = .20$; 550–600 msec: $F_{2, 32} = 8.03$, $p < .005$, $\eta_p^2 = .33$) but not in L2 (500–550 msec: $F_{2, 32} < 1$; 550–600 msec: $F_{2, 32} < 1$). Further pairwise comparisons showed that there was a significant difference between positive and neutral words ($p = .02$) during 500–550 msec time window. The differences between positive and neutral words ($p < .01$) and between positive and negative words ($p = .045$) were both significant during the 550–600 msec time window, indicating that positive words elicited a smaller positivity at centro-parietal sites than both neutral and negative words in L1.

In order to better understand emotional word processing differences between two languages, we conducted several additional analyses only within L2. First, three analyses of the EPN component were conducted in the time windows from 350 to 500 msec where previous studies suggested a delayed EPN effect. Second, six analyses of the LPC component were also conducted from 400 to 700 msec. For these additional analyses, the same electrodes were selected as in the previous analyses. We found that in the time window of 400–450 msec, the emotional valence effect was significant in L2 ($F_{2, 32} = 4.42$, $p = .03$, $\eta_p^2 = .21$), but pairwise comparisons did not reveal any significant difference among words of different emotional valances.

To better demonstrate the emotional effects during the time window of 400–450 and 450–500 msec in L2, we conducted an additional analysis on the mean amplitude of the 400–500 msec time window. A significant emotional valence effect was revealed ($F_{2, 32} = 4.14$, $p = .03$, $\eta_p^2 = .21$), and pairwise comparisons showed that neutral words elicited marginally

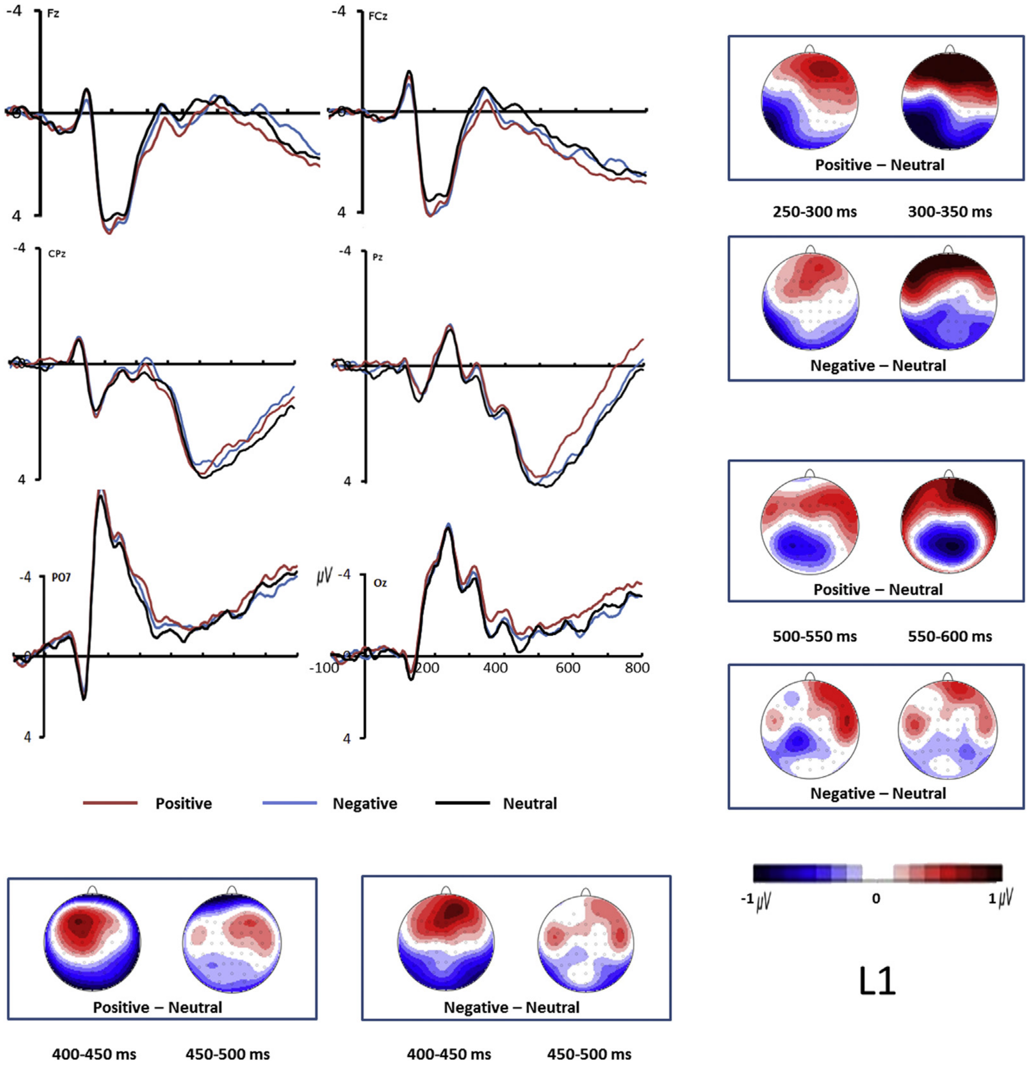

Fig. 1 – ERPs elicited by positive, negative, and neutral words in L1 are shown by two representative electrodes from the frontal, central, and occipital sites. The scalp distributions on the right show difference waves between positive and neutral, and between negative and neutral words at the time windows of 250–300 msec, 300–350 msec, and 500–550 msec and 550–600 msec. The scalp distributions of the 400–450 msec and 450–500 msec time windows provide comparisons for the emotional effect during the same time windows in L2.

larger negativities than positive words did ($p = .08$). Other than the significant language main effect reported in the Supplementary material, no other effects reached significance.

2.1.3. *Discussion*

The purpose of the ERP experiment was to examine the temporal course of processing emotional words in bilinguals. First of all, participants responded to words in L1 faster than to those in L2, suggesting they are more proficient in their L1. This is consistent with the language profile of the participants in the current study, who live in their L1 environment and are dominant in their L1. We also found that participants responded more quickly and accurately to positive words in L1 than neutral words, showing the typical emotional effect in a native language (e.g., Schacht & Sommer, 2009a; Scott et al., 2009). More interestingly, positive words in L2 also received higher accuracies compared to both neutral and negative words, although this processing advantage was not observed in reaction times.

The ERP results showed that only positive words in L1 elicited a larger negative-going waveform on the posterior sites (EPN) during both 250–300 msec and 300–350 msec time windows compared to neutral words. This is consistent with previous ERP studies of emotional word processing among monolingual speakers (Herbert et al., 2008; Hofmann et al., 2009; Kissler et al., 2007; Schacht & Sommer, 2009a, 2009b; Scott et al., 2009), and confirms that the emotional words used in the present study, as in the monolingual studies, automatically captured attention in participants' native language, which likely facilitated the processing. The EPN was more profound in positive words, which accords with our behavioral results showing that positive words have the shortest reaction time and highest accuracy.

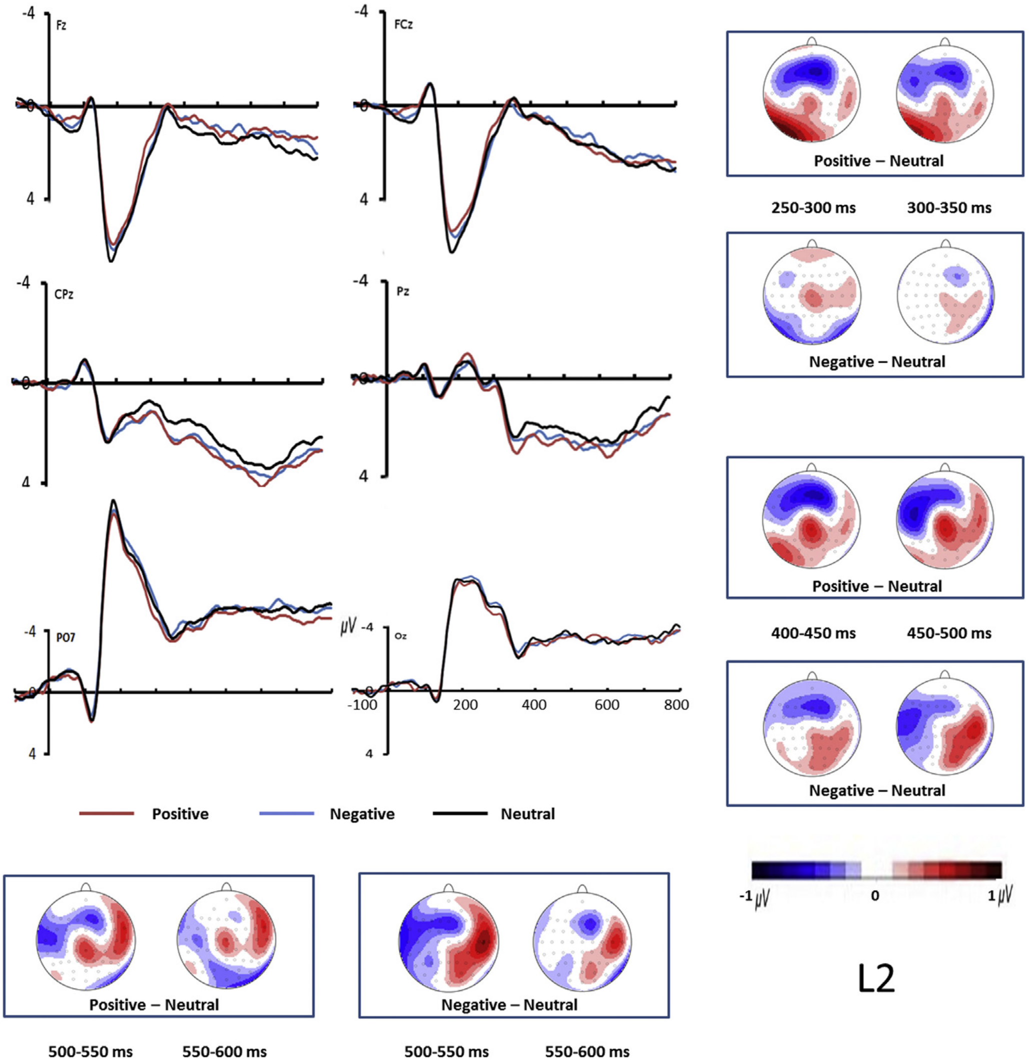

Fig. 2 – ERPs elicited by positive, negative, and neutral words in L2 are shown by two representative electrodes from the frontal, central, and occipital sites. The scalp distributions show difference waves between positive and neutral, and between negative and neutral words at the time windows of 250–300 msec, 300–350 msec, 400–450 msec and 450–500 msec. The scalp distributions of the 500–550 msec and 550–600 msec time windows provide comparisons for the emotional effect during the same time windows in L1.

Moreover, in the late time windows of 500–550 and 550–600 msec, the late positive component (LPC), which is seen as a correlate of elaborate processing (Bayer et al., 2010; Fischler & Bradley, 2006; Schacht & Sommer, 2009b), showed smaller amplitudes for positive words than for neutral words in L1. This finding is consistent with some of the previous studies (Citron, 2011; Hinojosa et al., 2009), whereas (most) other studies found that emotional words elicited larger LPC than neutral words (e.g., Herbert et al., 2006; Kissler et al., 2009; Schacht & Sommer, 2009a, 2009b). A possible explanation is that neutral words require more effort than positive words in the late time window due to the lack of automatic attention in the early time window (Citron, 2012), which is consistent with the current finding that neutral words elicited smaller EPN in earlier time windows.

The emotional valence effect was revealed in 400–500 msec time windows in L2 such that neutral words trended to induce lager negativities than positive words did. This finding suggests that for late but relatively proficient bilinguals, emotional words in L2 could also elicit emotional effects. However, this emotional effect is relatively late when compared to the effect in L1, and differs from the delayed EPN effect in bilinguals' L2 observed in two previous studies (Conrad et al., 2011; Opitz & Degner, 2012). First, the emotional effect in the current study occurred around 400–500 msec after the stimulus onset, which is 100 msec later than the delayed EPN effect reported in previous studies. Second, the scalp distribution map of this emotional effect does not resemble an EPN effect which is characterized by an enhanced negativity in the posterior sites. Therefore, it seems that we did not find the same delayed EPN effect as two previous studies of bilingual emotional word processing (Conrad et al., 2011; Opitz & Degner, 2012). One possible explanation is that the bilingual participants in the studies by Conrad et al. (2011) and Opitz and Degner (2012) had either lived in or were currently living in their L2 speaking countries. This immersion experience may have enabled them to have more automatized responses to L2 emotional words. In contrast, the participants in the current study were relatively proficient bilinguals who had only learned their second language in the classroom and had never been to their L2 speaking countries, thus they were less likely to have the rapid and automatized process for L2 emotional words. This explanation is consistent with the finding that only bilinguals who were immersed in an L2 environment and used L2 frequently showed the automatic valence priming effect in their L2 (Degner, Doycheva, & Wentura, 2012).

Instead, this weak L2 emotional effect around 400–500 msec in the current study might resemble a N400 effect, as indicated by scalp distribution maps. Unlike the EPN or LPC effect, N400 is not a common component reported in emotional word processing research. Nevertheless, Herbert et al. (2008) reported smaller N400 amplitudes for pleasant words opposed to unpleasant words in the first language, and suggested the attenuated N400 for pleasant words reflected facilitated semantic integration. It is likely that reduced N400 for emotional words (mainly for positive words) in the current study indicates that bilinguals accessed and integrated semantic content more easily when the emotional content was positive. This result is also reflected by the behavioral finding that positive words in L2 received higher accuracy than neutral words.

Interestingly, an overall opposite pattern were observed in the ERP effects across two languages. This opposite pattern is most apparent during the 250–300 and 300–350 msec time windows, which is characterized by larger posterior negativity for L1 emotional words and larger posterior positivity for L2 emotional words. While previous studies on bilingual emotional word processing suggest that processing L2 emotional words is only quantitatively different (i.e., slower) from processing L1 emotional words (Conrad et al., 2011; Opitz & Degner, 2012), this opposite pattern in the current study, together with the lack of enhanced EPN effect for L2 emotional words, might suggest that the emotional effects in L1 and L2 are the consequence of qualitatively different processing, at least for late bilinguals. However considering our bilinguals had less immersion experience than those in the two previous studies, it is also plausible that bilinguals would gain more native-like automatized processing as their proficiency or immersion experience increases.

2.2. *Experiment 2*

In the fMRI experiment, another group of Chinese–English bilinguals from the same population as in Experiment 1 were recruited. The same materials and a similar experimental design without repeating a subset of words, were used. This study was approved by the Institutional Review Board of the Imaging Center for Brain Research of Beijing Normal University.

2.2.1. *Methods*

2.2.1.1. Participants. Twenty-three Chinese–English bilinguals from the same population sampled in Experiment 1 participated in the fMRI study. All participants were right-handed and had normal or corrected-to-normal vision. None of them reported any depression or mood disorders. All participants gave informed consent prior to the experiment. One participant was excluded because the range of head movement exceeded 1 voxel. The remaining twenty-two participants (16 females, $M = 22.41$, $SD = 1.56$) started to learn English after the age of seven ($M = 10.95$, $SD = 2.21$). Neither their CET-4 scores ($M = 546.36$, $SD = 37.99$) nor self-ratings (Chinese: $M = 8.51$, $SD = 1.12$; English: $M = 5.53$, $SD = 1.46$, $t_{21} = 9.25$, $p < .001$) differed from the participants in the Experiment 1 ($ts_{37} < 1.5$, $ps > .1$). The working memory span (Operational Span score: $t_{37} = -1.03$, $p > .1$) and attentional control ability (Simon score: $t_{37} = 1.79$, $p = .082$) of participants from two experiments did not differ from each other. Overall, the participants for these two experiments were well matched.

2.2.1.2. Materials. The same materials from Experiment 1 were used. Two sets of materials (each containing 30 positive, 30 negative, 30 neutral and 90 pseudowords) were created for each language. These sets were matched for frequency, stroke number, length, valence and arousal ($ps > .1$). Each participant was presented with one set of Chinese words and one set of English words. The sets of materials chosen from each language were mutually exclusive; that is, for any given word presented in one of the two languages, its translation equivalent was not present in the set for the other language. Additionally, we included 90 baseline stimuli (consisted of four plus signs: ++++) in each language. Prior to the experiment, the same practice material from Experiment 1 was used.

2.2.1.3. Procedure. In the fMRI experiment, an event-related design was employed. Chinese and English were presented in two separate runs. The order of runs was counterbalanced across participants. Each run started with a 6 sec waiting screen. Additionally, two baseline stimuli, which were not included in the data analysis, were presented immediately after the waiting screen and after the experimental trials, resulting in a total of 274 trials in each run. During each run, the stimuli (words, pseudowords, or baseline stimuli) were presented in pseudorandom order in black on a white background for 1000 msec and followed by a 1000 msec blank screen. When presented with a baseline stimulus, no response was required. When presented with words or pseudowords, participants were asked to make a lexical decision as quickly and accurately as possible by pressing the special buttons using their left or right thumb. The response hand for words and pseudowords was counterbalanced across participants. A practice session of 10 trials was provided before the formal experiment to ensure that participants understood the instructions. After the formal experiment, they were asked to stay in the scanner for eight minutes for a structural scan. Subsequently, the participants performed the operational span and Simon tasks outside the scanner. The experiment lasted for approximately one hour.

2.2.1.4. Behavioral data. The same criteria as in Experiment 1 for excluding both absolute and relative outliers was used and the mean response times and accuracies for each participant were submitted to a 2 (Language: L1 and L2) × 3 (Emotional valence: positive, negative, and neutral) repeated measures ANOVA.

2.2.1.5. fMRI data acquisition and analyses. Both functional and structural images were acquired by a Siemens 3.0 T Sonata whole-body MRI scanner. Participants' heads were secured to minimize movements. For both Chinese and English sessions, 274 interleaved T2-weighted echo planar images were acquired. Every functional image comprised 33 transversal slices of 4 mm thickness with 3.1 × 3.1 mm^2 in-plane resolution (TR/TE/flip angle = 2,000 msec/30 msec/90; field of view = 200 × 200 mm^2, matrix size = 64 × 64). All structural 3D T1-weighted images comprised 144 interleaved sagittal slices of 1.33 mm thickness with 1.3 × 1.0 mm^2 in-plane resolution (TR/TE/flip angle = 2,530 msec/3.39 msec/7, respectively; field of view = 256 × 256 mm^2, matrix = 256 × 256).

Imaging data were pre-processed and analyzed with the Statistical Parametric Mapping software (SPM 8, Welcome Department of Imaging Neuroscience, London, UK: http://www.fil.ion.ucl.ac.uk/spm). The first and last two functional images in each run were excluded. Then, the images were slice-time corrected. After realigning the images to the first image of each session to correct for head motion, the images were coregistered with the structural images and normalized to Montreal Neurological Institute (MNI) template. Finally, the images were smoothed with a 6-mm full-width at half maximum Gaussian filter.

First level analysis: The data were analyzed in a participant-specific manner. Task effects were estimated according to the general linear model. To exclude low frequency confounds, the data were high-pass filtered using a set of discrete cosine basis functions with a cutoff period of 128. The movement parameters derived from the realignment stage were incorporated as nuisance variables. The contrasts of interest at the first level were each of the stimuli categories relative to pseudowords. These contrasts were used in the second-level, random-effect analysis.

Second level analysis: In order to explore functional activation during processing emotional words in two languages, we performed a 2 (Language: L1 and L2) × 3 (Emotional valence: positive, negative, and neutral) full factorial ANOVA. Further analyses were also performed if the main effect of emotional valence or interaction between language and emotional valence was significant. Activation is reported for clusters reaching a spatial threshold of at least 10 contiguous voxels each at a significance threshold of $p < .0005$ (alphasim corrected for multiple comparisons).

Region of interest (ROI) analysis was conducted by using MarsBaR toolbox (http://marsbar.sourceforge.net). Based on previous monolingual studies where some brain areas were found to be involved in emotional valence processing, the right amygdala (25,−7,−11) (Maddock et al., 2003), the bilateral superior frontal gurys (−10,54,36, and12,48,51) (Herbert et al., 2009; Kuchinke, et al., 2005), the bilateral cingulate cortex (−9,28,35, and 16,−38,6) (Maddock et al., 2003) and the left occipital gyrus (−20,−96,−4) (Herbert et al., 2009) were defined as ROIs (radius = 5 mm). All the coordinates reported here were using MNI coordinates. For each ROI 2 (Language: L1 and L2) × 3 (Emotional valence: positive, negative, and neutral) ANOVAs were performed. Again, only the main effect of emotional valence and the interaction between language and emotional valence will be reported here and the main effect of language will be provided in the Supplementary material.

2.2.2. *Results*

2.2.2.1. Behavioral results. The behavioral results for Experiment 2 are shown in Table 2. For the reaction time analyses, the main effect of language was significant ($F_{1,\ 21} = 125.78$, $p < .001$, $\eta_p^2 = .86$), indicating that words in L1 were responded to faster than those in L2. The main effect of emotional valence was significant ($F_{2,\ 42} = 8.58$, $p < .005$, $\eta_p^2 = .29$). Further comparisons revealed shorter reaction times for positive words compared to both neutral ($p < .05$) and negative words ($p < .01$). Although the interaction between language and emotional valance was not significant ($F_{2,\ 42} < 1$), two separate one-way ANOVAs were performed within each language to better examine the emotional effect in L1 vs. in L2. In L1, the emotional valence effect was significant ($F_{2,\ 42} = 7.09$, $p < .005$, $\eta_p^2 = .25$), and pairwise comparisons showed that positive words received faster responses than both negative ($p = .013$) and neutral words ($p < .01$). In L2, the emotional valence effect was marginally significant ($F_{2,\ 42} = 3.09$, $p = .061$, $\eta_p^2 = .13$). However, pairwise comparisons did not reveal any differences between emotional and neutral words ($ps > .1$).

For the accuracy analyses, the main effect of language was significant ($F_{1,\ 21} = 7.24$, $p < .05$, $\eta_p^2 = .26$), indicating that accuracy for words in L1 was higher than for those in L2. The main effect of emotional valence was also significant ($F_{2,\ 42} = 10.23$, $p < .005$, $\eta_p^2 = .33$). Further comparisons showed that accuracy for positive words was higher than for neutral words ($p < .001$) and negative words ($p < .005$). The interaction between language and emotional valence was significant ($F_{2,\ 42} = 8.09$, $p < .005$, $\eta_p^2 = .28$). Further comparison revealed a significant effect of emotional valence in L2 ($F_{2,\ 42} = 12.76$, $p < .001$, $\eta_p^2 = .38$) with higher accuracy rates for positive than neutral ($p < .001$) and negative words ($p < .005$).

2.2.2.2. fMRI results. The neuroimaging results for the main effect of emotional valence, and the interaction between language and emotional valence are shown in Fig. 3, and Tables 3 and 4. The main effect of emotional valence was located in the right superior parietal lobe (BA 7). Further analysis revealed that activation in this brain area was greater for neutral word than for both positive ($p = .023$) and negative words ($p = .023$). The interaction between language and emotional valence was significant in the left cerebellum.

Table 2 – Mean reaction times (RT) and accuracy rates (ACC) in the fMRI experiment (standard deviation in parentheses).

	L1		L2	
	RT (msec)	ACC (%)	RT (msec)	ACC (%)
Positive	610 (59)	97.91 (3.36)	691 (62)	98.09 (2.49)
Negative	629 (68)	96.63 (4.57)	708 (79)	93.09 (5.93)
Neutral	628 (66)	97.45 (2.81)	700 (73)	93.45 (4.27)

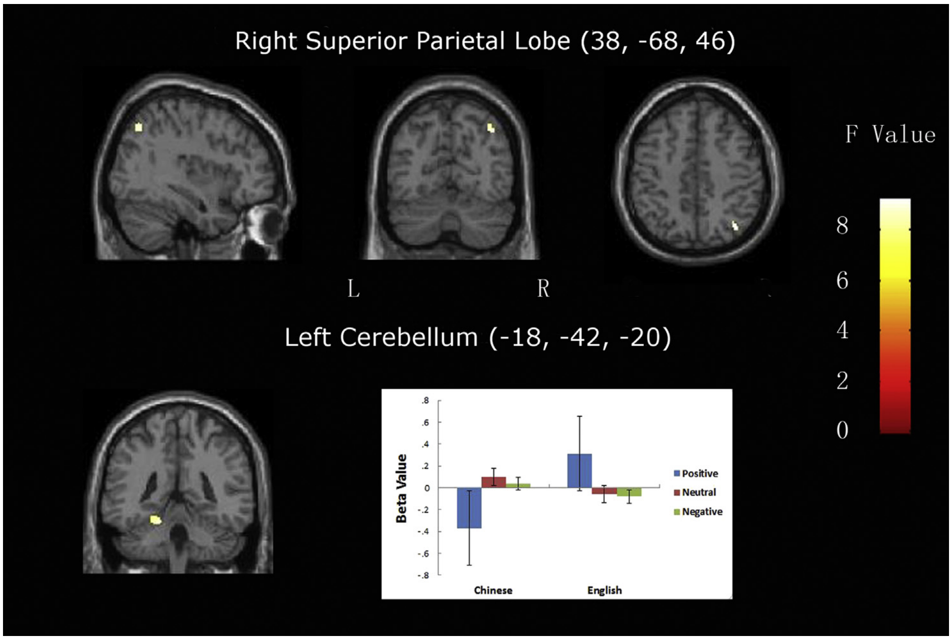

Fig. 3 – The main effect of emotional valence and the interaction between language and emotional valence from the whole brain analysis are presented at a threshold of $p < .0005$ (corrected) with a spatial extend threshold of 10 contiguous voxels. The upper panel displays the cortical activation in the right superior parietal lobe, and the lower panel shows the interaction between language and emotional valence in the left cerebellum with the beta values (with standard error bars) for words of three emotional valances in each language.

Further comparisons showed that the emotional valence main effect was significant both in L1 ($F_{2,\ 42} = 5.62$, $p = .012$, $\eta_p^2 = .21$) and in L2 ($F_{2,\ 42} = 5.27$, $p = .015$, $\eta_p^2 = .20$). Pairwise comparisons in each language showed that in L1, positive words had weaker activation than negative ($p = .047$) and marginally weaker activation than neutral words ($p = .055$); in L2, positive words had stronger activation than neutral words ($p = .026$).

In the ROI analyses, the emotional valence effect was significant in the left superior frontal gyrus (MNI: −10,54,36, BA 9; $F_{2,\ 42} = 3.44$, $p = .045$, $\eta_p^2 = .14$). Pairwise comparison showed that activation for negative words was greater than neutral words ($p = .043$). The interaction between language and emotional valence was significant in the middle occipital gyrus (MNI: −20,−96,−4, BA 18; $F_{2,\ 42} = 8.10$, $p < .005$, $\eta_p^2 = .28$). Post-hoc comparisons revealed that the emotional valence main effect was only significant in L1 ($F_{2,\ 42} = 7.34$, $p < .005$, $\eta_p^2 = .26$), showing that positive words had smaller activation than both neutral ($p = .018$) and negative words ($p < .01$). On the contrary, the emotional valence effect was not significant in L2 ($F_{2,\ 42} = 1.73$, $p = .19$, $\eta_p^2 = .076$) (see Fig. 4).

2.2.3. *Discussion*

The goal of Experiment 2 was to investigate the neural correlates of processing emotional words in bilinguals' two languages. Behaviorally, the reaction time measure showed that the emotional effect was only in L1, while the accuracy measure showed an emotional effect only for positive words in L2. This result indicates that the processing advantage for positive emotional words can be evident in both languages of late bilinguals. However, the effects were manifested in different measures (reaction time vs. accuracy), which is similar to the behavioral findings in Experiment 1.

In the fMRI data, two brain areas have found to respond to the emotional content of words, however, the specific roles that they play in emotional information processing is not fully

Table 3 – The main effect of emotional valence.

Brain regions	Cluster size	BA	MNI coordinate			F value	*p* value
			x	y	z		
R_ Superior Parietal Lobe	14	7	38	−68	46	9.22	<.0005

Table 4 – The interaction between language and emotional valance.

Brain regions	Cluster size	BA	MNI coordinate			F value	*p* value
			x	y	z		
L_ Cerebellum	19		−18	−42	−20	9.84	<.0005

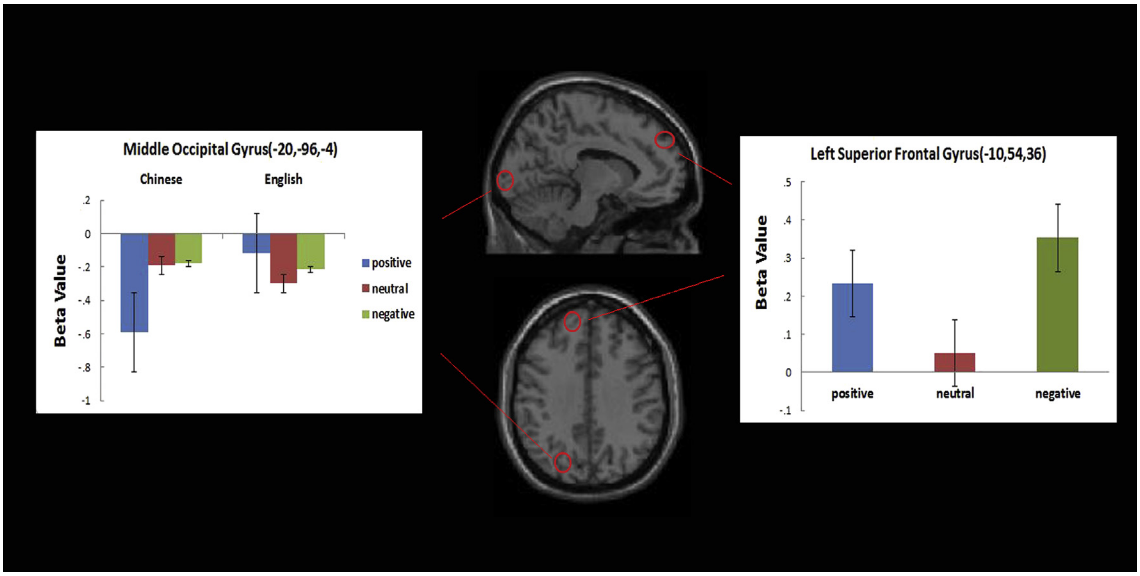

Fig. 4 – ROI analyses show the interaction between language and emotional valence in the left middle occipital gyrus with the beta values for positive, negative and neutral words in two languages (left panel), and the main effect of emotional valence in the left superior frontal gyrus with the beta values in positive, negative and neutral words (right panel).

understood. The first area is the left superior frontal gyrus (SFG), where we found that negative words had stronger activation than neutral words. This is consistent with the results for monolinguals by Beauregard et al. (1997). However, a similar monolingual study employing the lexical decision task found that only positive words induced greater activation in the left superior frontal gyrus (Kuchinke et al. 2005). These findings, along with those of the present study, might indicate that the left superior frontal gyrus may be involved in processing both positive and negative words. The second area is the superior parietal lobe, in which we found that neutral words show greater activation than both positive and negative words. Some previous studies (Herbert et al., 2009; Kensinger & Schacter, 2006) have found differentiated activation for emotional and neutral words in the superior parietal lobe. However, the role of this area in processing emotional information is somewhat unclear. In Kensinger and Schacter (2006), emotional words showed greater activation in this area than neutral words, while neutral words were found showing greater activation than emotional words in Herbert et al. (2009). Similar to Herbert et al. (2009), we also found that neutral words had stronger activation than emotional words, suggesting that the superior parietal lobe is sensitive to emotional content manipulation, but more studies are needed to understand the role of the superior parietal lobe in emotion processing.

More importantly, the interaction between language and emotional valence in the left cerebellum and the middle occipital gyrus reveals that neural activation of processing emotional words might vary in L1 and in L2. In the middle occipital gyrus, positive words in L1 showed weaker activation than both neutral and negative words. This result confirms the finding in Herbert et al. (2009), indicating a crucial role of visual cortex in recognizing emotionally salient stimulus. However, the same region was found to show greater activation for emotional words than neutral word in Herbert et al. (2009). These opposite results might be explained by the experimental task difference between the current study and Herbert et al. (2009). In Herbert et al. (2009), a silent reading task was used and participants were not required to make any response but to read the stimulus on the screen. As there was no task requirement or time pressure, it is possible that participants spent time evaluating the semantic connotation of each word carefully. Therefore, the greater activation in the visual cortex reflects greater attention is engaged in the processing of emotional words. In contrast, in the current study participants were asked to make lexical responses as quickly and accurately as possible when they saw a stimulus, and the lexical decision does not require them to process emotional information explicitly. In this case, the activation in the visual cortex might indicate the amount of effort that is needed for recognizing the stimulus in a timely manner. The automatized access of emotional connotation in one's first language might help to facilitate the process of word recognition, resulting in less activation in the visual cortex for L1 positive words. On the contrary, this same visual area seems to be unresponsive to emotional content in L2. The lack of differentiation for emotional words and neutral words in L2 in this area seems to concord with the absence of the EPN in the ERP experiment since the visual cortex has been suggested to be associated with the EPN effect (Schupp, Junghöfer, Weike, & Hamm, 2003).

Furthermore, in the left cerebellum, two opposite patterns of the hemodynamic response to the emotional content of words were found across bilinguals' two languages. While positive words showed weaker activation than neutral words in L1, positive words in L2 had greater activation than neutral words. Recent studies suggest that the cerebellum may not be involved only in motor control but also in non-motor functioning such as emotional processing and emotional experience (Canli et al. 2004; Turner et al. 2007; see Schutter & Van Honk, 2005 for review), language processing (see Murdoch, 2010 for review), attention (Allen, Buxton, Wong, & Courchesne, 1997), and executive function (Schmahmann & Sherman, 1998). In the language processing domain, the cerebellum has been found to play a specific role in semantic processing (McDermott, Petersen, Watson, & Ojemann, 2003; Noppeney & Price, 2002; Xiang et al., 2003). Although most studies have found that the right cerebellum plays a more dominant role in semantic processing (e.g., Noppeney & Price, 2002; Xiang et al., 2003), the role of left cerebellum is still significant (Murdoch & Whelan, 2007). Therefore, in regard to the opposite patterns in emotional words in L1 and L2, it is possible that attenuated activation for L1 positive words indicates greater ease of accessing L1 emotional information due to the automatized recognition. On the other hand, greater activation for L2 positive words reflects enhanced semantic information processing. This enhanced processing might compensate for less automatized access to L2 emotional words, which enables L2 positive words to be recognized more accurately.

However, we didn't find any significant main effect of emotional valence or the interaction between language and emotion in ROI analyses of the amygdala, the ventral striatum, or the orbitofrontal cortex. This may be due to task demands in the present study. The activation of the amygdala was found in studies when participants were asked to evaluate emotional valence explicitly (Lewis, Critchley, Rotshtein, & Dolan, 2007; Maddock et al., 2003; Tabert et al., 2001), but not in other studies when emotional valence was task-irrelevant (Beauregard et al., 1997; Cato et al., 2004; Kuchinke et al., 2005; Moseley, Carota, Hauk, Mohr, & Pulvermüller, 2011). Moreover, activation of the cingulate cortex was more likely to be observed in studies involving cognitive control and assessment, such as in the emotional Stroop task or modified Stroop tasks (George et al., 1994; Isenberg et al., 1999; Whalen et al., 1998), and emotional valence evaluation task (Maddock & Buonocore, 1997; Maddock et al., 2003; Posner et al., 2009; Tabert et al., 2001). A similar study using the lexical decision task did not find any activation of the amygdala or cingulate cortex (Kuchinke et al., 2005). A possible reason for a lack of activation in these areas is that emotional arousal in the context of an LDT is relatively lower than other tasks that require emotional evaluation. Future studies might use different tasks which require more direct emotional processing to investigate the involvement of the amygdala and cingulate cortex in emotional information processing.

A recent fMRI study found that L1 and L2 emotional text both elicited emotional responses effectively (Hsu, Jacobs, & Conrad, 2015). Hsu et al. (2015) also found that emotional processing in L1 was more profound and had more distinctive patterns. This finding, which was not present in the current study, might rise from the types of emotional materials that were used in two studies. In Hsu et al. (2015), emotional passages were used, which were likely to induce more profound emotional activation than single word processing in the current study. The more profound activation in L1 might result from the accumulating effect of slight emotional activation difference between two languages, which is difficult to detect in single word context.

3. General discussion

Subjective reports and previous psychophysiological studies have found that bilinguals' emotional activation is weaker in L2 than in L1 (e.g., Dewaele, 2004; Harris et al., 2006). However, several studies of online processing (Eilola et al., 2007; Sutton et al., 2007) have failed to find any differences in reaction time for emotional words between L1 and L2. Due to its high temporal or spatial resolution, both ERP and fMRI techniques have been used to investigate the neural mechanisms of emotional word processing in monolinguals (see Citron, 2012 for a review). So far, two published ERP studies (Conrad et al., 2011; Opitz & Degner, 2012) and one fMRI study (Hsu et al., 2015) have examined bilingual emotional word processing. The present study, for the first time, used both ERPs and fMRI along with behavioral measures to investigate the time course and the underlying neural mechanism of emotional word processing in L1 and L2. Overall, emotional words in L1 and L2 showed advantages over neutral words in either processing speed or recognition accuracy. Additionally, different ERP components as well as different brain activation patterns were found to be associated with L1 and L2 emotional effects respectively, revealing a complicated picture of emotional word processing in bilinguals. These neural findings might provide insights for understanding behavioral processing advantages in bilinguals' two languages.

For positive words in L1, an enhanced EPN was found when compared with neutral words. Considering the enhanced EPN effect is often interpreted as the rapid and automatic attention capture (e.g., Kissler et al., 2007), it is very likely that this automatic attention capture resulted in decreased reaction time of processing positive words. This rapid and automatic process might also be associated with reduced activation in the occipital area and the left cerebellum for L1 positive words, indicating a less effortful process in general. In L2, a smaller N400 and greater activation in the left cerebellum was found for emotional words when compared to neutral words. It is possible that increased activation in the left cerebellum enhanced semantic processing, resulting in an overall easier semantic integration and semantic retrieval for positive words. Because of the easier integration and retrieval, L2 positive words were recognized with higher accuracies and associated with a smaller N400. Regardless, emotional words in L2, unlike those in L1, show neither neural signatures indexed for automatic processing nor decreased reaction time.

It is worth noting that we observed relatively consistent behavioral outcomes for emotional words in L1 and in L2 across two experiments. In L1, the emotional word processing advantage was mainly reflected by decreased reaction times (and also by increased accuracies in Exp. 1), while in L2 the emotional effect was only reflected by increased accuracies. These patterns might suggest that emotional word advantages in L1 and in L2 resulted from different processes. Robust evidence from previous emotional word studies in monolinguals indicates that emotional words in one's native language rely on automatic attention capture to achieve facilitated processing (e.g., Kissler et al., 2007; Schacht & Sommer, 2009a), and this finding was confirmed in the present study as well.

By contrast, emotional content seems to help late bilinguals better recognize emotional words in their second language. As discussed earlier, one possibility is due to facilitated semantic access to positive content in L2 emotional words (e.g., Herbert et al., 2008). Another possibility is that positive words in L2 were better memorized and thus appear to be more familiar to bilinguals, although the objective frequencies were well controlled between emotional and neutral words. Using the memory and recall task, previous studies have demonstrated that bilinguals (even late bilinguals) remember and recall emotional words better than neutral words in their L2, as in their L1 (e.g., Ayçiçeği & Harris, 2004; Ferré et al., 2010). The present study, using a lexical decision task, also showed that L2 emotional words are better recognized than L2 neutral words. This finding further supports that L2 emotional words may be represented differently than L2 neutral words in bilinguals' mental lexicon (Pavlenko, 2008). As a result, they are identified more accurately than neutral words.

Another interesting finding to note is that the emotional word processing advantages in the current study were driven mainly by positive words, while there was no reaction time, accuracy or brain activity difference between negative and neutral words. This finding seems inconsistent with some previous studies in which processing advantage has been found for both positive and negative words (e.g., Schacht & Sommer, 2009a, 2009b). In a large sample study, Kousta, Vinson, and Vigliocco (2009) showed that emotion words, regardless of their valences, were processed faster and more accurately than neutral words. Nevertheless, Kousta and colleague suggested that the facilitation effect for both positive and negative words does not necessarily imply the same underlying processing. Several previous studies found a processing advantage for only positive words (Carretie et al., 2008; Hinojosa, Méndez-Bértolo, & Pozo Hofmann, 2010; Hofmann et al., 2009; Kissler & Koessler, 2011; Kuchinke et al., 2005). These studies, together with the current study, indicate a more robust processing advantage for positive words. A possible explanation of this advantage is that healthy participants are generally in neutral or slightly pleasant moods in their daily lives, which is congruent with the information that positive words provide. Accordingly, this congruence may facilitate the processing of positive words (Erickson et al., 2005). It is also possible that participants adopt different strategies for processing positive and negative words to avoid the negative feelings (Wu & Thierry, 2012).

4. Conclusions

The present study provides evidence for the temporal course and neural mechanisms for processing emotional words in two languages of bilinguals. Converging temporal and spatial neural evidence suggests that L1 emotional words rely on a more rapid and more automatized process while L2 emotional words might rely on easier semantic access to achieve the emotional word processing advantage.

Acknowledgments

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2015.06.002.

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