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Research article

Electrophysiological evidence of lexical processing impacted by foreign language reading anxiety

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ABSTRACT

Extensive studies have been conducted on the impact of foreign language reading anxiety on reading, primarily focusing on pedagogy and behavior but lacking electrophysiological evidence. The current study aimed to investigate the influence of foreign language reading anxiety on reading and its underlying mechanisms. The results revealed a negative correlation between foreign language reading anxiety and foreign language reading performance, irrespective of the native language. Adults with low levels of foreign language reading anxiety (LFLRA) demonstrated a significant difference in early lexical component N170 amplitude between foreign and native languages. However, this effect was not observed in adults with high levels of foreign language anxiety (HFLRA). In terms of N170 latency, HFLRA showed a longer N170 for the foreign language compared to the native language. Furthermore, the N170 effects were predominantly localized over the left occipitotemporal electrodes. Regarding N400 latency, a significant difference was found in LFLRA individuals between foreign and native language processing, while HFLRA individuals did not exhibit this difference. These findings suggest that HFLRA individuals experience inefficient lexical processing (such as orthography or semantics) during reading in foreign language.

1. Introduction

Fluent reading in a second language has become a fundamental ability for successful academic and social life. However, a significant number of individuals experience reading anxiety, commonly known as foreign language reading anxiety (FLRA). FLRA refers to the perceptions of apprehension, discomfort, or unease that individuals experience when reading foreign language (FL) texts ([1], p.1362). FLRA has a relatively high prevalence [2]; [3], affecting approximately one-third of Chinese-English bilinguals [4]; [5]; [6]. Converging evidence indicates that FLRA has a detrimental impact on reading performance [7]; [8,9], with higher levels of anxiety associated with decreased reading accuracy and slower reading speed [10–12].

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FLRA has often been conceptualized as anxiety specifically related to the non-native language [13]; [3]; [14]; [6,15]. Liu [16] observed that participants with high FL anxiety demonstrated poorer performance in the FL verb-noun naming task and exhibited a higher heart rate compared to those with low FL anxiety, while there was no difference between the two groups in the native language (NL) naming task. MacIntyne & Gardener (1991) also shed light on the specific nature of foreign language anxiety. The correlation results indicated that the anxious individuals' feelings were significantly associated with FL reading performance but not with NL reading performance [17].

In bilingual studies, foreign and native languages share common neurophysiological mechanisms for reading. The word quality framework [18,19] suggests that word reading involves the explicit representation (identification of lexical features) and integration of these lexical features (conceptual representation). Fluent reading requires the ability to rapidly and accurately identify words, which can be even faster than auditory recognition. Hence, researchers often employ event-related potential (ERP) techniques known for the excellent temporal resolution [20] to investigate lexical reading. In lexical decision tasks, two ERP components are typically associated with different sub-processes of reading. The first component is the occipitotemporal N170, which is consistently elicited by visual words, peaking around 200 ms after stimulus onset [21–25]. The N170 reflects early stages of lexical or sub-lexical orthographic processing during word reading [26]; [27]; [24] and is typically left-lateralized [23]. The second reading-related component is the centro-parietal N400 [28,29], which reflects semantic processing and peaks around 400 ms after stimulus onset. The N400 is sensitive to lexical properties, particularly semantic relatedness [30,31,32], and indicates the integration of semantic information during reading. Reading-related N170 and N400 components can be observed across languages [33]; [34]; [35]; [27]. Both foreign and native languages can evoke N170 and N400 responses when visual words or word-related information is detected [15,27,36].

Indeed, both foreign and native languages rely on certain neural substrates such as N170 and N400. However, the activation of different writing systems often leads to varying degrees of dependence and performance in orthographic and semantic processing activities during word recognition [37,38]; [39,40]. For instance, Chinese reading is associated with a bilateralized or even right-lateralized N170 while English reading shows a more left-lateralized N170 [41,42]. The lateralized N170 could be attributed to the distinct orthographic information across languages [43]; [44]. As for the N400 component, English exhibits a weaker and/or longer N400 compared to Chinese [33,45]. Chinese-English bilinguals, compared to English monolinguals, demonstrate a reduced N400 response for English word pairs that shared a character in their Chinese translation [46]. As previously noted, FLRA exclusively affect foreign language reading performance, with no significant impact on native language [17]. In our current study, we hypothesized that this exclusionary effect on foreign language may step from FLRA's influence on reading-related neural components that exhibit language differences, such as N170 and N400. Otherwise, both languages could potentially be affected.

Taken together, this study aimed to examine whether and how FLRA affects the neurophysiological processes involved in bilingual reading. To achieve this, we conducted lexical decision tasks to compare N170s and N400s in response to native and foreign languages between HFLRA and LFLRA. We recruited Chinese-English adults with various levels of FLRA and assessed their behavioral and electrophysiological responses during the Chinese character and English word recognition tasks. Behaviorally, we anticipated that HFLRA would exhibit slower and less accurate retrieval of FL words compared to LFLRA. Electrophysiologically, HFLRA individuals may demonstrate distinct temporal brain wave patterns associated with lexical representation when compared to LFLRA individuals. By analyzing the N170s and N400s in response to NL and FL, we would be able to investigate the specific characteristics of these ERP components in individuals with HFLRA.

2. Materials and methods

2.1. Participants

Sixty-eight Chinese-English bilinguals (34 females; mean age = 20.9, standard deviation [SD] = 2.17) participated in the current study. The screening procedure included two stages: 1) 201 undergraduates participated in the online tests for the first stage. All the participants were Chinese-English bilinguals and had been learning English for more than 7 years. They were tested by three reading anxiety scales (detailed information about these tests were in the following section). We summed up the z-scores of each scale and arranged the scores in ascending order. Participants scoring in the top 25 % and the last 25 % were defined as individuals with high (HFLRA) and low levels of reading anxiety (LFLRA) respectively. We adopted the 25 % cut-off point based on the criteria for screening State-Trait anxiety, which has been previously used [47–49].

2) On the second stage, one exclusion criterion was used. To control for the potential influence of reading anxiety from the native language (e.g., Chinese), we excluded the participants scoring out of one SD in the Chinese Reading Anxiety Scale (CRAS). Finally, 34 participants in HFLRA and 34 participants in LFLRA were recruited in the current study.

All participants were right-handed as assessed by the Chinese version of the Handedness Questionnaire. They had normal or corrected-to-normal vision and had no history of neurological abnormalities or language impairments. This experiment was approved by the Local Ethics Committee at Shenzhen University and all participants provided informed consent before the experiment. They were compensated for their participation.

2.2. Reading anxiety tests

To measure foreign language reading anxiety, three widely used FLRA scales have been employed, including the Foreign Language Reading Anxiety Scales (FLRAS, [50]), English as a Foreign Language Reading Anxiety (EFLRA [51,52]), and Reading Anxiety Source Questionnaire (RASQ [53]). FLRAS primarily focuses on anxiety caused by the content of reading materials itself, such as anxiety related to unfamiliar writing systems and unfamiliar cultures (Cronbach's alpha = 0.86). EFLRAI specifically targets English as a foreign language (EFL) learners, and it expands on FLRAS by including two additional factors beyond the reading itself, namely anxiety associated with the readers themselves (e.g., language proficiency) and that caused by teachers (e.g., teaching methods; Cronbach's alpha = 0.93, [54]; [6]; [55]). Lastly, the RASQ also targets EFL learners, but it emphasizes reading processes, such as time constraints during reading, and a lack of reading skills [53]. To comprehensively represent the level of FLRA, the participants were screened by the three scales.

To measure native language reading anxiety, the Chinese Reading Anxiety Scale (CRAS) was utilized. Adapted from FLRAS [50], the CRAS replaced the term "foreign language" with "native language" in the scale items, specifically targeting Chinese-English bilinguals. For example, the statement "When reading English, I get nervous and confused when I don't understand every word" was modified to "When reading Chinese, I get nervous and confused when I don't understand every character". Cronbach's alpha is utilized to assess the reliability of the questionnaire, providing an index ranging between zero ($\alpha = 0$) and one ($\alpha = 1$). A Cronbach's alpha value of 0.7 or higher is considered good for instruments comprising ten or more items. In the case of the CRAS questionnaire, the reliability analysis yielded a Cronbach's alpha score of 0.72.

2.3. *General anxiety tests*

To distinguish between general anxiety and FLRA, participants also completed the State-Trait Anxiety Inventory (STAI [56]). STAI (Cronbach's alpha = 0.85) consists of State Anxiety Inventory (SAI) and Trait Anxiety Inventory (TAI). A higher total score on the scale indicates a higher level of anxiety.

2.4. *Reading-related tasks*

To measure word reading efficiency in both languages, participants were required to complete five reading-related tasks. We utilized the Rapid Automatized Naming (RAN, [57,58]) task and the Woodcock Reading Mastery Tests (WRMT, [59]) for English. The RAN task consists of two parts, with each part containing 40 different letters. Participants were instructed to read the letters as accurately and quickly as possible. The final score was determined by averaging the scores obtained from completing two versions of this task. Additionally, WRMT includes Word Identification (WI, real word reading test) and Word Attack (WA, pseudowords reading test). The number of correctly pronounced words was regarded as an index for reading performance.

For Chinese, the Chinese Character Recognition (CCR) test and the Chinese Reading Efficiency (CRE) test [60,61] were utilized. In the CCR test, participants were presented with 150 Chinese characters selected from 3500 less frequently used characters. These characters were ordered in increasing difficulty (i.e., decreasing word frequency). Participants were required to read the characters one by one until they were unable to correctly read 15 consecutive characters. In the CRE test, participants were given the task of reading as many as possible of 200 Chinese characters within 1 min [60,61]. This task was performed twice and the score was determined by calculating the average number of characters accurately read across the two times.

2.5. *Stimuli*

The stimuli consisted of 120 high-frequency Chinese disyllabic words sourced from the Chinese Lexical Database (CLD; [62]) and 120 high-frequency English disyllabic words with six-to-seven letters obtained from Intelligent Web-base Corpus (iWeb). To assess the familiarity of the stimuli, we enlisted the help of 60 independent participants who were not English majors. These participants were asked to rate the familiarity of all the stimuli on a seven-point scale, ranging from never (1) to frequent (7). A Paired-sample *t*-test revealed no significant difference in familiarity between the Chinese and English words (mean familiarity: 5.01 vs. 5.01; $t = 1.544$, $p = 0.125$), as outlined in the Appendix. For half of the words in each stimulus type, we created pronounceable pseudo-words by modifying the configuration of the real words by the orthographic rules of Chinese and English. All stimuli were presented in lowercase letters of the 'Times New Roman' font, with a font size of '48′, in white ink on a black background at the center of the screen. The stimuli were carefully adjusted for luminance and root mean square contrast using Adobe Photoshop. The visual distance was approximately 100 cm in front of a computer screen.

2.6. *Procedure*

Participants were instructed to engage in a lexical decision task. Each trial commenced with the presentation of a white fixation cross (+) for 1000 ms. Following a stimulus duration of 2000 ms, participants were required to determine whether the visual stimulus presented was a real word or a pseudo-word by pressing the 'F' or 'J' key, respectively. They were encouraged to respond with both speed and accuracy ('F' for real words with the left index finger and 'J' for pseudo-words with the right index finger, which were counterbalanced across participants). Once participants made their responses, the stimulus disappeared from the screen. The experimental procedure encompassed a total of 240 trials, presented in a pseudo-randomized order to ensure that stimuli of the same type did not appear consecutively. Each stimulus was presented once throughout the experiment. Regular breaks were provided to participants after every 30 trials to allow for rest. The duration of the task was approximately 20 min. Before commencing the actual experiment, participants completed 8 practice trials to familiarize themselves with the task requirements and response keys. The presentation of stimuli was controlled using E-Prime 3.0 software (Psychology Software Tools, Inc., Pittsburgh, PA).

2.7. EEG recordings

The electroencephalogram (EEG) data were continuously recorded from 64 cap-mounted Ag/Ag–Cl electrodes (Brain Products, Munich, Germany) mounted on an elastic cap that was located in the Standard International 10–20 System. To monitor eye movements and blinks, an additional electrode was positioned below the right eye to record the electrooculogram (EOG). The data acquisition was performed at a sampling rate of 1000 Hz. The reference electrode was located at FCz and the impedance of all electrodes was maintained below 5 kΩ.

2.8. Data analysis

We conducted a mixed repeated-measures ANOVA with Group Type (HFLRA/LFLRA) as the between-subject factor and Language Type (English/Chinese) as the within-subject factor. Considering the significant effects of gender and language proficiency on the groups, gender and language proficiency were conducted as covariates in the analysis.

The behavioral data were analyzed for accuracy and reaction time (RTs) from the stimulus onset. RTs from the incorrect answers and RTs that were implausibly long or short (i.e., 200 ms below or above the mean reaction time of 1500 ms) were excluded from the analysis.

Off-line processing of EEG data was collected using EEGLAB [63] toolboxes in Matlab. The data underwent offline high-pass and low-pass filtering between 0.1 Hz and 30 Hz. Channels identified as problematic through visual inspection were removed and the data were re-referenced to an average reference. ERPs were calculated for each participant within an epoch spanning from 200 ms before to 2000 ms after the onset of the stimuli. Baseline correction was applied relative to the −200 to 0 ms pre-stimulus time. Following manual removal of any remaining artifacts, independent component analysis (ICA) using the Infomax Restricted algorithm was employed to identify and remove ICA component artifacts related to eye movements, muscle artifacts, or other artifacts [63,64]. Only trials with correct responses were included in the analysis and valid trials were required to have a minimum of 120 trials. Epochs containing artifacts exceeding a threshold of ±100 μV during the recording period were excluded from the analysis. Finally, the artifact-free EEG data were segmented into epochs ranging from 200 ms (for the baseline correction) to 1000 ms.

We conducted an analysis of peak amplitudes and latencies for the occipitotemporal N170 and central-parietal N400 components. The ERPs were averaged based on waveform patterns observed across different sets of electrodes, guided by grand-mean topographies and relevant literature [65,66,67]. The N170 peaks were identified within the time window of 160–220 ms after stimuli onset and the electrode sites of P7, PO7, O1, P8, PO8, and O2 were examined to analyze the effects of orthographic processing. On the other hand, the N400 peak was observed within the time window of 300–500 ms, and the electrode sites of Fz, FCz, Cz, CPz, and Pz were analyzed to investigate the effect of semantic processing (see Fig. 1).

3. Results

3.1. Behavioral data

First, a chi-square test was conducted to examine the gender differences between HFLRA and LFLRA, yielding a significant result ($\chi 2 = 5.882$, $p < 0.05$). However, no significant differences were found between the two groups in terms of age, STAI, and CRAS (see Fig. 2 in the Appendix).

Regarding reading performance outside the scanner, we observed significant group differences in RAN, WRMT, and CCT test, but not in the CRE test (see Table 1).

Concerning the high correlation between English and Chinese tests ($r = 0.443$, $p < 0.001$), we included the language proficiency

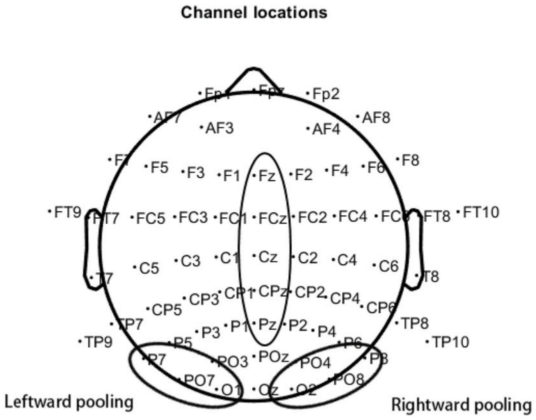

Fig. 1. Channel locations. The posterior occipitotemporal electrodes were clustered on the left and right hemispheres together, while the centro-parietal electrodes were clustered in the central region. ERPs analysis was applied over these electrode sites.

test as a covariate to account for the interaction of the two languages. The results revealed that after controlling for English reading ability, the previously observed significant group differences in Chinese proficiency tests became non-significant ($ps > 0.5$). However, when each Chinese proficiency test was taken as a covariate, thce group differences in English tests remained significant ($ps < 0.01$). This suggests that there were indeed significant differences in English tests between HFLRA and LFLRA, while the group differences in Chinese tests may be influenced by the high correlation between Chinese and English achievement.

For accuracy, we observed a significant main effect of Language (F (1,66) = 280.931, $p < 0.001, \eta_p^2 = 0.810$). Participants demonstrated higher accuracy in Chinese (97.62 % ± 2.69 %) compared to English (80.47 % ± 9.58 %). Additionally, a significant main effect for Group was found (F (1,66) = 12.059, $p < 0.01, \eta_p^2 = 0.154$). Furthermore, a significant interaction between Group and Language was observed (F (1,66) = 16.156, $p < 0.001, \eta_p^2 = 0.197$). Follow-up simple effect tests showed that participants with HFLRA exhibited relatively lower accuracy in English (76.38 % ± 8.27 %, t (66) = −3.892, $p < 0.001$, *Cohen's d* = 0.953) compared to LFLRA (84.59 % ± 9.11 %). However, no significant group effect was observed in Chinese (97.62 % ± 2.26 % vs. 97.62 % ± 3.09 %, p = 1.000, the figure in the Appendix).

Concerning the reaction time, the main effect of Language was significant (F (1,66) = 579.760, $p < 0.001, \eta_p^2 = 0.898$). Participants exhibited faster reaction times for Chinese characters (685.510 ms ± 77.795 ms) compared to English words (912.011 ms ± 125.647 ms). However, neither the significant interaction between the Group and Language (F (1,66) = 0.033, p = 0.856) nor a main effect of the Group was observed (F (1,66) = 0.264, p = 0.609, see Fig. 2).

Considering the significant group effect observed in gender, Chinese tests, and English tests, we conducted an additional analysis using these factors as covariates separately. Remarkably, even after controlling for gender and language abilities, all the main effects of Language and Group, as well as the interaction between Language and Group, remained significant. These findings indicated that the observed results were robust and not affected by gender or language abilities.

3.2. *N170 measurement*

An apparent N170 component was observed across electrodes and languages in both groups, peaking at approximately 200 ms after stimulus onset. The ERP wave forms and topographic plots for each condition were illustrated in Fig. 3.

3.2.1. *Amplitude analysis*

For the peak amplitude of N170, we found a significant main effect of Language (F (1,66) = 6.722, $p < 0.05, \eta_p^2 = 0.092$). Participants exhibited less negative amplitudes for Chinese (−8.320 ± 5.169) compared to English (−9.050 ± 4.980). Moreover, a significant interaction effect (F (1,66) = 5.424, $p < 0.05, \eta_p^2 = 0.076$) was observed over the left hemisphere. Follow-up simple effect tests revealed that for each language task, there were no significant differences between HFLRA and LFLRA. For LFLRA, a significant effect was observed for different languages (Chinese: 8.422 ± 4.764 vs. English: 9.807 ± 4.866, $p < 0.01$, *Cohen's d* = 0.287), whereas no significant effect of Language Type for HFLRA (Chinese: 8.218 ± 5.616 vs. English: 8.293 ± 5.050, p = 0.853).

Additionally, over the right hemispheres, we observed only a significant main effect of Language (F (1,66) = 19.686, $p < 0.001, \eta_p^2 = 0.230$). The overall N170 amplitude for English words (−8.277 ± 5.085) was relatively more negative compared to Chinese characters (−7.179 ± 4.940). However, the main effect of Group (F (1,66) = 1.750, p = 0.190) and the interaction did not reach a significant level (F (1,66) = 0.557, p = 0.458, see Fig. 4).

3.2.2. *Latency analysis*

For peak latency of N170, we found a significant main effect of Language Type (F (1,66) = 5.032, $p < 0.05, \eta_p^2 = 0.071$), revealing that the N170 latency for Chinese characters (190.926 ± 15.441) was earlier compared to English words (193.647 ± 12.127). Additionally, we observed a significant two-way interaction effect between Language and Group (F (1,66) = 5.629, $p < 0.05, \eta_p^2 = 0.079$) over left occipital-temporal sites. Simple effect tests revealed that there was a significant group difference in processing Chinese characters (HFLRA: 187.235 ± 15.849 vs. LFLRA: 194.617 ± 14.310, t (66) = −2.016, $p < 0.05$, *Cohen's d* = 0.489) but no significant

Table 1
Average performance on cognitive and demographic tasks of HFLRA and LFLRA and group differences (*t*-test).

	HFLRA (n = 34)		LFLRA (n = 34)		*t*-value
	M	SD	M	SD	
Age	20.79	1.99	21.09	2.35	−0.55
Sex (female/male)	12/22		22/12		
Chinese tests					
Chinese Character Recognition test	−0.15	1.04	0.15	0.94	−1.27
Chinese Reading Efficiency test	−0.23	1.12	0.23	0.80	−2.00[b]
English tests					
Rapid Automatized Naming	0.41	1.05	−0.41	0.75	3.71[a]
Word Identification	−0.49	1.07	0.49	0.61	−4.70[a]
Word Attack	−0.42	0.84	0.42	0.97	−3.83[a]

Note.

[a] $p < 0.001$.

[b] $p < 0.05$.

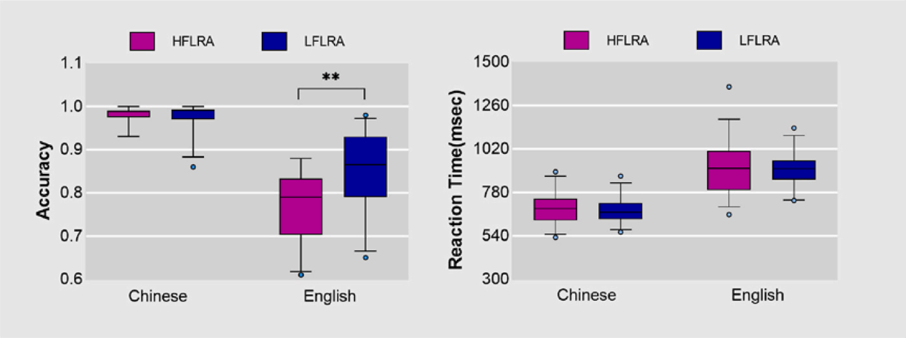

Fig. 2. Behavioral performance (mean accuracy and response time) in different languages (Chinese and English) and groups (HFLRA, the high foreign language reading anxiety group; LFLRA, the low foreign language reading anxiety group). *Note:* **$p < 0.01$.

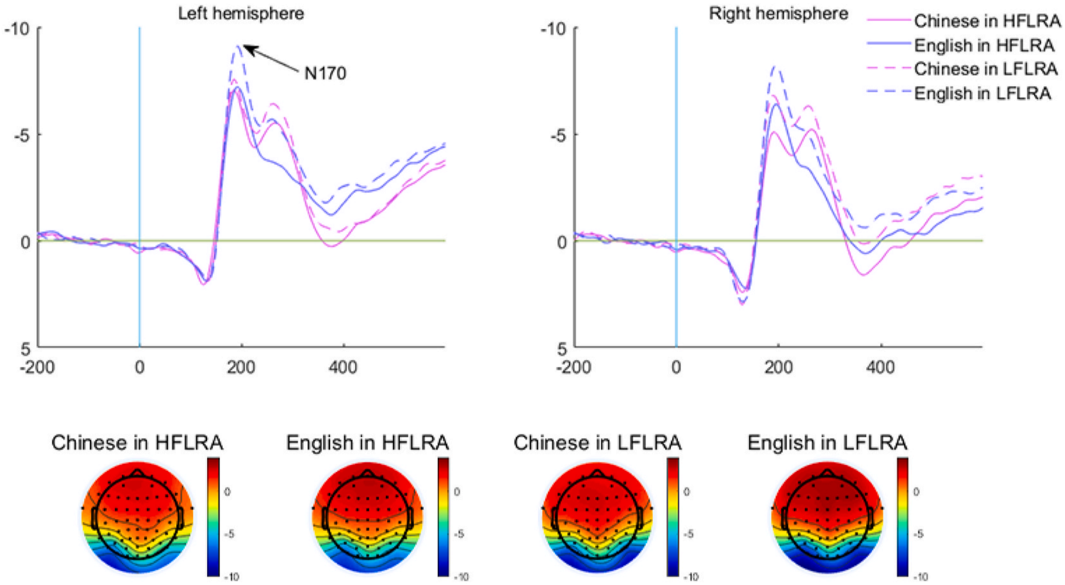

Fig. 3. The N170 component time-locked to Chinese characters and English words averaged in HFLRA and LFLRA groups. ERPs were calculated by averaging data at the left occipitotemporal electrodes of P7, PO7, and O1, and the right occipitotemporal electrodes of P8, PO8, and O2 separately. The y-axis is in μV with negative plotted up. The x-axis is in ms. Topographic plots of N170 effects collapsed across tasks in HFLRA and LFLRA groups in the 160–220 ms time windows.

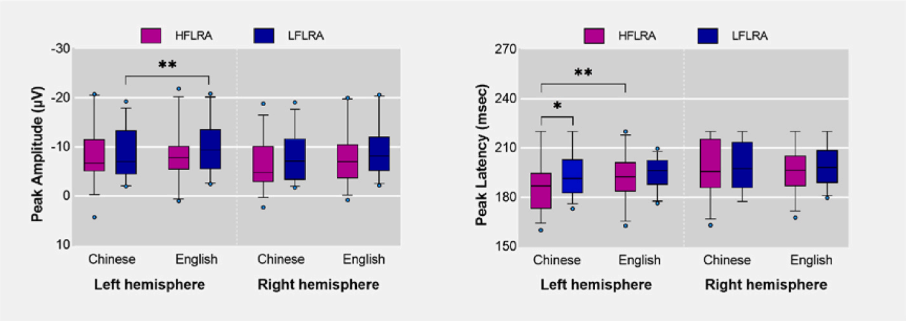

Fig. 4. Illustrations of the peak amplitude and latency of N170 of the averaged ERPs over the left and right occipitotemporal cortex under Chinese and English conditions for two groups. *Note:* **$p < 0.01$; *$p < 0.05$.

group difference in processing English words (HFLRA: 192.833 ± 14.241 vs. LFLRA: 194.460 ± 9.717, $p = 0.584$). We observed a significant language difference in the HFLRA group (Chinese: 187.235 ± 15.849 vs. English: 192.833 ± 14.241, $p < 0.01$, *Cohen's d* = 0.372) but not in the LFLRA group (Chinese: 194.617 ± 14.310 vs. English: 194.460 ± 9.717, $p = 0.927$). No significant effects were observed over the corresponding right sites (see Fig. 5).

Similarly, when gender, Chinese tests, and English tests were added as covariates, most of the significant interaction effects between Language and Group Type for N170 amplitude remained significant, and only one interaction effect became marginally significant ($p = 0.055$) when using Chinese tests as a covariate. As for N170 latency, the overall interaction over the left hemisphere remained significant, except when using English tests as the covariates.

3.3. N400 measurement

The N400 component was observed across electrodes and language in both groups at approximately 400 ms after stimulus onset. The ERP wave forms illustrating each condition can be seen in Fig. 5.

For the peak amplitude of N400, we only observed a significant main effect of Language Type ($F\,(1{,}66) = 15.899$, $p < 0.001, \eta_p^2 = 0.194$). The amplitude was found to be negative for Chinese (−1.748 ± 1.802) but positive for English (1.280 ± 1.703). Concerning peak latency, we also found a significant main effect of Language Type ($F\,(1{,}66) = 5.292$, $p < 0.05, \eta_p^2 = 0.074$), revealing that the latency for Chinese (374.262 ± 32.465) was longer than that for English (366.412 ± 33.25). Furthermore, there was a significant effect between Language and Group Type ($F\,(1{,}66) = 6.417$, $p < 0.05, \eta_p^2 = 0.089$). A simple effect analysis was conducted, which revealed no significant difference between the groups for both FL and NL tasks. For HFLRA, there was no significant effect of Language Type on latency (Chinese: 369.988 ± 35.822 vs. English: 370.782 ± 34.433, $p = 0.870$). However, for LFLRA, there was a significant effect of Language Type (Chinese: 378.535 ± 28.619 vs. English: 362.041 ± 31.932, $p < 0.01$, *Cohen's d* = 0.544), with the longer latency for Chinese compared to English (see Fig. 6).

4. Discussion

The present study aimed to investigate the impact of FLRA on reading performance from a neurobiological perspective. The study utilized lexical decision tasks to compare the reading-related electrophysiological markers (N170 and N400) during bilingual reading between individuals with HFLRA and LFLRA. At the behavioral level, HFLRA exhibited poorer reading performance in the foreign language compared to LFLRA. Neurobiologically, significant language differences between HFLRA and LFLRA were observed in the early stage of orthographic processing, as reflected by N170 amplitude and latency over the left hemisphere. Additionally, LFLRA demonstrated a significant difference in N400 latency between foreign and native language processing, which was not observed in HFLRA. These findings indicated that HFLRA can influence different stages of lexical representation such as orthographic or semantic processing.

4.1. A lower accuracy in HFLRA in foreign lexical processing

As expected, a significant group difference in accuracy was observed during English lexical processing. Specifically, HFLRA exhibited significantly lower accuracy in identifying English words compared to LFLRA, while they showed similar levels of accuracy in identifying Chinese characters. This finding provided strong evidence for the notion that the high level of FLRA may specifically contribute to poorer reading performance in FL lexical processing. Furthermore, we observed that LFLRA and HFLRA also did not show significant remarkable differences in general anxiety tests, i.e., state anxiety test and trait anxiety test. Prior literature suggests that anxiety encompasses numerous sub-types including state anxiety, trait anxiety, and anxiety specific to a certain situation (such as fear of a specific object, e.g. math anxiety; [11,12]). Accordingly, FLRA could be a sub-type of anxiety symptom specific to foreign language

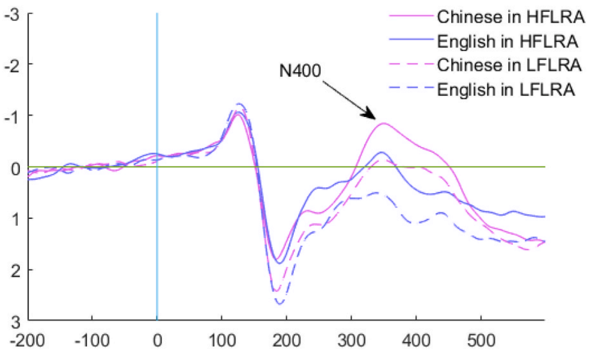

Fig. 5. The N400 component time-locked to Chinese characters and English words averaged in HFLRA and LFLRA groups in a 300–500 ms time window. Event-related potentials (ERPs) were calculated by averaging data at the centro-parietal electrodes of Fz, FCz, Cz, CPz, and Pz. The y-axis is in μV with negative plotted up. The x-axis is in ms.

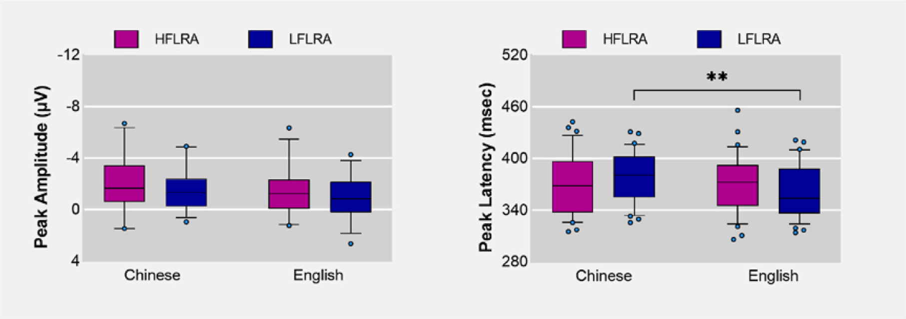

Fig. 6. Illustrations of the peak amplitude and latency of the averaged N400 over the centro-parietal cortex under Chinese and English conditions for two groups. Note: **$p < 0.01$.

reading situation, and is distinct from general anxiety. Hence, it is crucial to differentiate between various sub-types in future studies examining the influence of anxiety on behavioral performance, especially in academic contexts.

Interestingly, no significant group differences were found regarding response time during English word processing in the current study. In terms of reaction time, previous studies reported mixed group effects. For example, a recent study found that individuals with high social anxiety had a significantly faster speed of information processing than individuals with low social anxiety [68]. On the contrary, other studies reported longer reaction times in individuals with high anxiety [69,70][71]. In the case of foreign language anxiety, Liu [16] found no significant group differences in response time during the FL verb-noun naming task. The inconsistency between studies could be attributed to the differences in experimental design. The tasks varied across studies, including emotion recognition [68,72], muscular activities in response to auditory stimuli [69], verbal naming [16], as well as pre- and post-match performance comparisons in sports studies [70]. In contrast to these studies, our study employed a classic lexical decision task. This task presented challenges in both visual and semantic recognition, compared to the more commonly used facial emotion recognition tasks. Consequently, the participants in the current study may focus on the accuracy of word identification, potentially prioritizing the process of decoding lexical information over reading speed. In this way, group effect could be only manifested in accuracy but not in response time. Alternatively, lower accuracy coupled with comparable response time may reflect a speed-accuracy trade-off. Individuals with HFLRA are as fast as those with LFLRA, resulting in more errors given their general lower language proficiency. This, in turn, reinforces a self-fullfilling prophecy. Instead of slowing down to compensate, they attempt to maintain pace with LFLRA, which leads to increased errors and potentially further heightening their anxiety levels. Further research is needed to explore which of these two interpretations is more suitable.

4.2. *Impaired orthographic processing reflected by N170 in HFLRA*

For N170 peak amplitude, a significant interaction effect between language and anxiety was observed. LFLRA demonstrated significantly lower amplitude in NL compared to FL over the left occipitotemporal cortex, whereas this effect was not observed in HFLRA. This result was in line with previous research which reported a stronger N170 in response to FL in bilinguals or multilingual individuals [24], [36]. The occipitotemporal N170 component reflects lexical/sub-lexical processing across languages [73,74]. Previous research has shown that lexicon from different languages can initiate activation at the same time point [75] but with varying intensities depending on language proficiency [76–78]; [79]; [80–82]. Since FL proficiency is typically lower than native language in unbalanced bilinguals, more cognitive resources are required to activate FL, resulting in stronger neural activity [40,78]. Additionally, for bilinguals recruited in the current study, foreign language (i.e., English) is less frequently used compared to native language (i.e., Chinese), which may also result in greater neural response when it is processed. This may also explain the language difference observed in LFLRA in terms of N170 amplitude. The current result consolidates the asymmetry and parallel activation of visual lexical processing between the native and non-native languages.

In contrast to LFLRA, HFLRA did not show a significant language difference in N170 peak amplitude. However, a significant language effect was reflected in the latency, with a longer N170 latency for the foreign language. Similar results have been observed in individuals with reading difficulties, where no orthographic effects were manifested in N170 amplitude but a significant latency delay in latency was observed [80], indicating less efficient and slower processing of orthographic information in individuals with dyslexia [79,81]. In the current study, we also observed a prolonged N170 latency for FL in HFLRA, suggesting that HFLRA might also have difficulties in orthographic processing. With a high anxiety level, HFLRA may allocate more neural resources for emotional processing, consequently leading to sub-optimal performance in orthographic processing of the foreign language.

Interestingly, the significant N170 differences between NL and FL found in HFLRA and LFLRA were only observed in the left occipitotemporal electrode sites. N170 in responses to words has been known to be typically left-lateralized [22,23], supposedly due to the visual word form area within the left occipitotemporal cortex which is sensitive to words while literacy [83]; [84,85]; [86]. Neuroimaging studies have consistently shown that the left occipitotemporal cortex plays a critical role in visual word recognition and the analysis of letters and orthography [87]; [88,89]. According to the phonological mapping hypothesis, left-lateralized N170 has been suggested to reflect automatic spelling-to-sound mapping (for review see [83]). The significant differences of left-lateralized

N170 observed in our study indicated that FLRA primarily affected the automatic visual analysis of lexical processing, especially the area related to orthography processing rather than general visual processing.

4.3. A shorter N400 latency during foreign language processing in LFLRA

For N400, no significant interaction effect was observed in its amplitude. Instead, a significant language difference in N400 latency was observed in LFLRA. Specifically, LFLRA showed a longer N400 for the native language compared to the foreign language. Similarly, this difference was also absent in HFLRA. The N400 component has been known to reflect later stages of lexical-semantic processing [90] and is associated with the integration of word and/or semantic-level information [91]. It has also been used as a biomarker to assess the severity of comprehension deficits in adults with aphasia and children with language impairments [92,93]. A longer N400 latency suggests a slower rate of semantic processing and limited integration with mental representation [94]. Unexpectedly, this finding is contrary to our initial expectations of the shorter latency for the native language compared to the foreign language, which demonstrated native language superiority [38]; [45,95]. The occurrence of this unexpected result may be related to language inhibition. Inhibitory control theory proposes that the target language actively suppresses the activation of the non-target language [75,82,96,97]. As individuals become more proficient in their native language, the inhibition of native language during FL processing may be stronger than the inhibition of the foreign language during NL processing [82,97]. Consequently, when switching from FL to NL, slower responses may be observed, as indicated by a longer N400 latency [98]; [99]. However, when anxiety is present, the level of inhibition of the native language during FL processing may be reduced due to limited cognitive resources. Hence, there was no clear distinction in inhibition control between the native and foreign language, as demonstrated by the absence of a language difference in N400 latency in HFLRA. This finding aligned with the observations made in the N170 component, where a shorter latency was noted in HFLRA compared to LFLRA during NL reading. Under conditions of high anxiety, individuals experience fewer switching costs compared to those with low anxiety, resulting in accelerating native language processing. The results observed in N400 showed that HFLRA exhibited language control deficits during the process of semantic information.

Results of the N170 and N400 components indicated that FLRA influenced both the early and late stages of word recognition in foreign language. In the early stages of lexical acquisition, such as visual orthographic processing, HFLRA individuals demonstrated a longer N170 latency to FL. This result suggested a reduction in neural resources for FL processing, leading to difficulties in FL orthographic processing. In the late stages of lexical processing, HFLRA individuals exhibited reduced inhibition strength for NL during FL processing, leading to a decreased switching cost for the native language, which affects semantic-related neural components, i.e., N400.

4.4. Implications of the current study

This study makes several notable contributions to the existing body of literature. First, it extends previous studies by providing electrophysiological evidence for the influence of FLRA on the lexical processing of foreign language. Previous studies on foreign language reading anxiety predominantly focused on behavioral aspects, with little knowledge about its neural basis in the brain and the specific time window of cognitive processing. To address this gap, our study utilized ERP technology with a high temporal resolution to provide a deeper insight into the cognitive and neural mechanisms underlying FLRA. Second, this study investigated the influence of affective factors on foreign language processing. While research on foreign language reading has primarily examined the impact of impaired cognitive processes, such as orthographic processing (potentially reflected by the N170 component) or semantic processing (associated with the N400 component), there is growing recognition of the significance of affective factors [100]; [101,102]; [71]. Our study aimed to bridge this gap by exploring the effects of reading anxiety on foreign language processing and contributing to shedding light on the intricate interplay between cognitive and affective factors. These insights have implications for the development of effective strategies to address language processing difficulties and enhance language learning experiences. Third, this study demonstrated that reading anxiety may affect different stages of lexical processing. It is well-established that anxiety exerts a significant influence on cognitive control, necessitating the allocation of substantial neural resources [40,78]. In our investigation, we observed that reading anxiety can impact various stages of lexical processing, including both the early automatic orthographic processing stages (reflected by N170) and the subsequent semantic processing stages (reflected by N400). These findings contribute to a deeper understanding of how reading anxiety influences language processing. Fourth, this study further evidences that foreign language reading anxiety is specifically associated with the impairment of orthography processing in foreign language, but not in native language. Additionally, it verifies that FLRA is different from general anxiety, affecting the linguistic related processing rather than general visual processing.

Finally, some limitations should be mentioned. Firstly, our sample consisted of college students. To further enhance the generalizability of the current study, it would be beneficial to include individuals of different age groups, especially those who are beginning readers and are in the early stages of foreign language acquisition. This extension would provide additional insights into the effects of FLRA. Secondly, this study primarily focused on lexical processing. Future investigations are required to investigate the impact of foreign language reading anxiety on sentence-level reading comprehension and processing.

5. Conclusion

The current study provides important electrophysiological evidence for the modulation of foreign language reading anxiety on bilingual reading performance which has been seldom investigated in the previous studies. Our findings shed light on the detrimental effects of FLRA at different stages of word recognition (orthographic and semantic processing), providing further evidence of the language-specific modulation. This study on the contributions of affective factors such as foreign language reading anxiety provided valuable insights into the mechanisms of bilingual word reading and foreign language reading anxiety.

Data availability statement

The data supporting the findings of this study are available upon reasonable request from the first author, Lina Li.

CRediT authorship contribution statement

Lina Li: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qianqian Yu:** Formal analysis. **Yuru Wang:** Methodology. **Zhihao Wang:** Writing – review & editing. **Xinyi Zhou:** Data curation. **Qing Guan:** Writing – review & editing. **Yue-jia Luo:** Resources, Funding acquisition. **Hehui Li:** Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

HFLRA	high foreign language reading anxiety
LFLRA	low foreign language reading anxiety
FL,	foreign language
NL,	native language
ERP	event-related potential
SAI	State Anxiety Inventory
TAI	Trait Anxiety Inventory
CRAS	Chinese Reading Anxiety Scale
FLRAI	Foreign Language Reading Anxiety (FLRAS)
FLRAII	English as a Foreign Language Reading Anxiety (EFLRA)
FLRAIII	Reading Anxiety Source Questionnaire;
RAN	Rapid automatized naming
WI	Word Identification
WA	Word Attack

Appendix

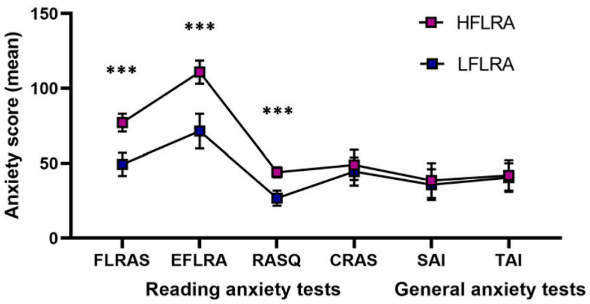

Fig. 2. Results of the reading anxiety tests and general anxiety tests. Reading anxiety tests included foreign language anxiety scales (FLRAS, EFLRA, RASQ) and Chinese Reading Anxiety Scale (CRAS), while general anxiety tests included State and Trait Anxiety Inventory (SAI, TAI). There were significant group differences in these three foreign language anxiety scales, while no group differences in CRAS, SAI, or TAI. *Note:* FLRAS, Foreign Language Reading Anxiety Scale; EFLRA, English as a Foreign Language Reading Anxiety; RASQ, Reading Anxiety Source Questionnaire; CRAS, Chinese Reading Anxiety Scale; SAI, State Anxiety Inventory; TAI, Trait Anxiety Inventory; HFLRA, high foreign language reading anxiety; LFLRA, low foreign language reading anxiety. The error bars represent the standard error of the mean. *** depicts significance $p < 0.001$.

Materials in bilingual lexical decision tasks.

Original Words for Pseudo Stimuli

No.	Chinese	Familiarity	No.	English	Familiarity
1	部分	6.28	1	balance	6.32
2	政府	6.26	2	degree	6.31
3	标志	6.16	3	purpose	6.29
4	特色	6.07	4	design	6.18
5	词汇	5.97	5	record	6.06
6	烹饪	5.84	6	survey	5.98
7	认知	5.82	7	signal	5.84
8	国旗	5.82	8	figure	5.82
9	案件	5.72	9	witness	5.81
10	野外	5.7	10	theory	5.69
11	原则	5.67	11	comment	5.68
12	近邻	5.62	12	journal	5.63
13	新品	5.62	13	release	5.61
14	供应	5.52	14	bicycle	5.61
15	加法	5.51	15	pattern	5.53
16	烤箱	5.41	16	reward	5.42
17	曾孙	5.41	17	debate	5.4
18	黎明	5.34	18	credit	5.34
19	评析	5.34	19	status	5.32
20	绿地	5.31	20	courage	5.31
21	边境	5.3	21	quarter	5.29
22	群落	5.26	22	profit	5.27
23	背影	5.25	23	guitar	5.24
24	牧场	5.25	24	reserve	5.27
25	冰袋	5.23	25	region	5.18
26	食粮	5.23	26	chapter	5.16
27	叮嘱	5.18	27	symptom	5.15
28	监控	5.15	28	tablet	5.15
29	探视	5.15	29	button	5.11
30	默契	5.11	30	justice	5.1
31	议员	5.11	31	climate	5.1
32	音响	5.08	32	decline	5.08
33	远洋	5.07	33	stomach	5.06
34	冥想	5.05	34	contest	5.03
35	情报	5	35	target	4.97
36	现货	5	36	carbon	4.97
37	实战	4.98	37	contract	4.92
38	猎枪	4.98	38	routine	4.92
39	错字	4.87	39	captain	4.89
40	韧性	4.85	40	garbage	4.89
41	药铺	4.84	41	monster	4.87
42	概略	4.8	42	blanket	4.82
43	幼体	4.8	43	border	4.76
44	彩礼	4.8	44	divorce	4.76
45	基数	4.77	45	closet	4.74
46	繁育	4.74	46	bullet	4.71
47	别针	4.72	47	genius	4.71
48	钓钩	4.72	48	turkey	4.69
49	滑坡	4.69	49	legend	4.68
50	财税	4.69	50	costume	4.68
51	前锋	4.67	51	protest	4.66
52	话机	4.15	52	finance	4.65
53	苯酚	4.13	53	virtue	4.16
54	麦芒	4.1	54	filter	4.15
55	清规	4.1	55	tunnel	4.11
56	律诗	4.38	56	warrior	4.11
57	海葵	4.05	57	column	4.29

(*continued on next page*)

(*continued*)

Original Words for Pseudo Stimuli

No.	Chinese	Familiarity	No.	English	Familiarity
58	笔调	3.98	58	suburb	4.1
59	宅第	3.89	59	council	4.06
60	窗棂	3.79	60	gallon	3.79

Word Stimuli

No.	**Chinese**	**Familiarity**	**No.**	**English**	**Familiarity**
61	世界	6.31	61	program	6.31
62	主意	6.31	62	service	6.31
63	艺术	6.26	63	message	6.24
64	参与	6.21	64	process	6.21
65	力量	6.08	65	promise	6.11
66	手臂	5.97	66	disease	6.1
67	耳机	5.85	67	measure	5.98
68	考生	5.69	68	general	5.9
69	出游	5.59	69	bottom	5.65
70	金牌	5.46	70	victim	5.63
71	班会	5.43	71	planet	5.58
72	宝石	5.39	72	demand	5.48
73	柜子	5.38	73	uspect	5.42
74	头衔	5.31	74	defeat	5.42
75	海龟	5.05	75	plastic	5.39
76	羔羊	5.02	76	budget	5.37
77	毛驴	5.02	77	studio	5.31
78	豪气	5.02	78	license	5.16
79	月底	4.89	79	balloon	5.1
80	皮蛋	4.82	80	fellow	5.08
81	门徒	4.8	81	butter	5.05
82	天梯	4.79	82	campus	5.02
83	主创	4.72	83	stadium	4.98
84	威望	4.72	84	diamond	4.98
85	重组	5.21	85	pursuit	4.97
86	痛觉	5.1	86	gender	4.9
87	国货	5	87	critic	4.9
88	生姜	4.64	88	silver	4.87
89	七窍	4.46	89	valley	4.87
90	鬼魅	4.44	90	defense	4.84
91	团练	4.44	91	motive	4.76
92	民意	5.08	92	welfare	4.74
93	远虑	4.69	93	bucket	4.69
94	司仪	4.77	94	romance	4.69
95	域名	4.7	95	fortune	4.68
96	盘古	4.64	96	protein	4.68
97	禅房	4.54	97	summit	4.65
98	御医	4.52	98	curtain	4.65
99	雄威	4.38	99	shelter	4.65
100	豆科	4.33	100	default	4.61
101	散步	6.13	101	terror	4.6
102	姑父	5.41	102	barrier	4.56
103	京剧	5.1	103	patent	4.55
104	黑洞	4.97	104	profile	4.55
105	缘分	4.85	105	parade	4.53
106	剑客	4.62	106	format	4.53
107	蟠桃	4.57	107	crisis	4.52
108	封条	4.57	108	resort	4.5
109	建树	4.57	109	particle	4.5
110	汗腺	4.56	110	volume	4.45
111	钢板	4.52	111	tissue	4.45
112	政纲	4.49	112	1consent	4.42
113	矿藏	4.49	113	sponsor	4.42
114	脑炎	4.46	114	powder	4.39
115	胶鞋	4.44	115	twitter	4.37
116	唇裂	4.44	116	dispute	4.37
117	端倪	4.41	117	venture	4.35
118	缆绳	4.41	118	pillow	4.34
119	祭坛	4.38	119	murder	4.23
120	黄铜	4.34	120	weapon	4.19

A Paired-sample t-test showed no significant difference in the familiarity between these Chinese and English words (Mean familiarity: 5.01 vs. 5.01, $t = 1.544$, $p = 0.125$).

References

[1] S.A. Capan, R. Pektas, An empirical analysis of the relationship between foreign language reading anxiety and reading strategy training, Engl. Lang. Teach. 6 (12) (2013) 181–188.

[2] X. Hu, X. Zhang, S. McGeown, Foreign language anxiety and achievement: a study of primary school students learning English in China, Lang. Teach. Res. (2021), https://doi.org/10.1177/13621688211032332.

[3] R. Li, Foreign language reading anxiety and its correlates: a meta-analysis, Read. Writ. 35 (4) (2021) 995–1018, https://doi.org/10.1007/s11145-021-10213-x.

[4] M. Liu, L. Xiangming, Changes in and Effects of Anxiety on English Test Performance in Chinese Postgraduate EFL Classrooms, vol. 2019, Education Research International, 2019, pp. 1–11, https://doi.org/10.1155/2019/7213925.

[5] M. Liu, R. Yuan, Changes in and effects of foreign language classroom anxiety and listening anxiety on Chinese undergraduate students' English proficiency in the COVID-19 context, Front. Psychol. 12 (2021) 1–15, https://doi.org/10.3389/fpsyg.2021.670824.

[6] Q.Q. Miao, J. Vibulphol, English as a foreign language reading anxiety of Chinese university students, Int. Educ. Stud. 14 (3) (2021) 64, https://doi.org/10.5539/ies.v14n3p64.

[7] Y.Z. Shi, Z.Q. Liu, Foreign language reading anxiety and its relationship to English achievement and gender, Journal of PLA University of Foreign Languages 29 (2006) 59–65.

[8] X. Zhang, Foreign language anxiety and foreign language performance: a meta-analysis, Mod. Lang. J. 103 (4) (2019) 763–781, https://doi.org/10.1111/modl.12590.

[9] L. Zhang, B. Wang, The relation between foreigners' Chinese anxieties and achievement and the teaching strategies, Lang. Teach. Linguist. Stud. 1 (2002) 36–42.

[10] Y. Teimouri, J. Goetze, L. Plonsky, second language anxiety AND ACHIEVEMENT: a meta-analysis, Stud. Sec. Lang. Acquis. 41 (2) (2019) 363–387, https://doi.org/10.1017/S0272263118000311.

[11] D. Francis, J.L. Hudson, S. Kohnen, L. Mobach, G.M. Mcarthur, The effect of an integrated reading and anxiety intervention for poor readers with anxiety, PeerJ 9 (4) (2021) e10987, https://doi.org/10.7717/peerj.10987.

[12] D.A. Francis, N. Caruana, J.L. Hudson, G.M. Mcarthur, The association between poor reading and internalizing problems: a systematic review and meta-analysis, Clin. Psychol. Rev. 67 (2018), https://doi.org/10.1016/j.cpr.2018.09.002.

[13] E.K. Horwitz, Foreign and second language anxiety, Lang. Teach. 43 (2010) 154–167.

[14] K.T. Macdonald, P.T. Cirino, J. Miciak, A.E. Grills, The role of reading anxiety among struggling readers in fourth and fifth grade, Read. Writ. Q. 37 (4) (2021) 382–394, https://doi.org/10.1080/10573569.2021.1874580.

[15] A. Rajab, W.Z.W. Zakaria, H.A. Rahman, A.D. Hosni, S. Hassani, Reading anxiety among second language learners, Procedia: Social and Behavioral Sciences 66 (2012) 362–369, https://doi.org/10.1016/j.sbspro.2012.11.279.

[16] C.H. Liu, The Cognitive Neurological Mechanism of Foreign Language Learning Anxiety on Second Language Production Unpublished doctoral dissertation Beijing Normal University, 2006. Unpublished doctoral dissertation.

[17] Peter MacIntyre, Language anxiety: Its relation to other anxieties and to processing in native and second languages, Language Learning 41 (1991) 513–534. https://doi.org/10.1111/j.1467-1770.1991.tb00691.x.

[18] C.A. Perfetti, L. Hart, The lexical quality hypothesis, Precursors of Functional Literacy. 11 (2002) 67–86.

[19] C.A. Perfetti, L. Verhoeven, Lexical Quality Revisited, 2017, pp. 51–67.

[20] D.M. Amodio, B.D. Bartholow, T.A. Ito, Tracking the dynamics of the social brain: ERP approaches for social cognitive and affective neuroscience, Soc. Cognit. Affect Neurosci. 9 (2014) 385–393, https://doi.org/10.1093/scan/nst177.

[21] S. Bentin, Y. Mouchetant-Rostaing, M.H. Giard, J.F. Echallier, J. Pernier, ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution, J. Cognit. Neurosci. 11 (3) (1999) 235–260, https://doi.org/10.1162/089892999563373.

[22] U. Maurer, D. Brandeis, B.D. McCandliss, Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response, Behav. Brain Funct. 1 (2005) 1–12, https://doi.org/10.1186/1744-9081-1-13.

[23] U. Maurer, J.D. Zevin, B.D. McCandliss, Left-lateralized N170 effects of visual expertise in reading: evidence from Japanese syllabic and logo-graphic scripts, J. Cognit. Neurosci. 20 (10) (2008) 1878–1891, https://doi.org/10.1162/jocn.2008.20125.

[24] Y.N. Yum, S.P. Law, C.F. Lee, M.S.K. Shum, Early event-related potentials differences in orthographic processing of native and non-native Chinese readers, J. Res. Read. 41 (3) (2018) 403–422, https://doi.org/10.1111/1467-9817.12115.

[25] Y.N. Yum, S.P. Law, Interactions of the age of acquisition and lexical frequency effects with phonological regularity: an ERP study, Psychophysiology 56 (10) (2019) e13433, https://doi.org/10.1111/psyp.13433.

[26] S. Araújo, L. Faísca, I. Bramão, K.M. Petersson, A. Reis, Lexical and phonological processes in dyslexic readers: evidence from a visual lexical decision task, Dyslexia 20 (1) (2014) 38–53, https://doi.org/10.1002/dys.1461.

[27] C.H. Hsu, Y.N. Wu, C.Y. Lee, Effects of phonological consistency and semantic radical combinability on n170 and p200 in the reading of Chinese phonograms, Front. Psychol. 12 (2021) 603878, https://doi.org/10.3389/fpsyg.2021.603878.

[28] D. Panizza, E. Onea, N. Mani, Early ERP evidence for children's and adult's sensitivity to scalar implicatures triggered by existential quantifiers (some), Front. Psychol. 12 (2021) 657408, https://doi.org/10.3389/fpsyg.2021.657408.

[29] P.B. Silva, D.G. Oliveira, A.D. Cardoso, P.G. Laurence, P.S. Boggio, E.C. Macedo, Event-related potential and lexical decision task in dyslexic adults: lexical and lateralization effects, Front. Psychol. 13 (2022) 852219, https://doi.org/10.3389/fpsyg.2022.852219.

[30] M. Kutas, K.D. Federmeier, Event-related Brain Potential (ERP) Studies of Sentence Processing, 2007, https://doi.org/10.1093/oxfordhb/9780198568971.013.0023.

[31] M. Kutas, K.D. Federmeier, Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP), Annu. Rev. Psychol. 62 (2011) 621–647.

[32] T.Y. Swaab, K. Ledoux, C.C. Camblin, M.A. Boudewyn, Language-Related ERP Components, 2012, https://doi.org/10.1093/oxfordhb/9780195374148.013.0197.

[33] J. Xue, B. Li, R. Yan, J.R. Gruen, T. Feng, M.F. Joanisse, J.G. Malins, The temporal dynamics of first and second language processing: ERPs to spoken words in Mandarin-English bilinguals, Neuropsychologia 146 (2020) 107562, https://doi.org/10.1016/j.neuropsychologia.2020.107562.

[34] J. Zhao, S. Li, S.E. Lin, X.H. Cao, S. He, X.C. Weng, Selectivity of N170 in the left hemisphere as an electrophysiological marker for expertise in reading Chinese, Neurosci. Bull. 28 (5) (2012) 577–584, https://doi.org/10.1007/s12264-012-1274-y.

[35] A. Charollais, A. Lempereur, V. Simon, C. Seraffin, R. Lalonde, M.H. Stumpf, M. Rebai, D. Bannier, ERP variabilities as a function of reading maturation, Neurophysiologie clinique = Clinical neurophysiology 46 (4–5) (2016) 313–315, https://doi.org/10.1016/j.neucli.2015.12.004.

[36] M. Naranowicz, K. Jankowiak, P. Kakuba, K. Bromberek-Dyzman, G. Thierry, In a bilingual mood: mood affects lexico-semantic processing differently in native and non-native languages, Brain Sci. 12 (2022) 316, https://doi.org/10.3390/brainsci12030316.

[37] S. Ardal, M.W. Donald, R. Meuter, S. Muldrew, M. Luce, Brain responses to semantic incongruity in bilinguals, Brain Lang. 39 (2) (1990) 187–205, https://doi.org/10.1016/0093-934x(90)90011-5.

[38] C.M. Weber-Fox, H.J. Neville, Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers, J. Cognit. Neurosci. 8 (3) (1996) 231–256, https://doi.org/10.1162/jocn.1996.8.3.231.

[39] Y. Liu, C.A. Perfetti, The time course of brain activity in reading English and Chinese: an ERP study of Chinese bilinguals, Hum. Brain Mapp. 18 (3) (2003) 167–175, https://doi.org/10.1002/hbm.10090.

[40] C.A. Perfetti, Y. Liu, Orthography to phonology and meaning: comparisons across and within writing systems, Read. Writ. 18 (2005) 193–210.

[41] Y. Yum, S. Law, N170 reflects visual familiarity and automatic sublexical phonological access in L2 written word processing, Biling. Lang. Cognit. (2021), https://doi.org/10.1017/S1366728920000759.

[42] Y.N. Yum, S.P. Law, N170 reflects orthographic uniqueness point effects in English among native Japanese and Korean readers, Neurosci. Lett. 743 (2021) 135568, https://doi.org/10.1016/j.neulet.2020.135568.

[43] H. Li, J. Wu, R.A. Marks, H. Huang, L. Li, L. Dong, G. Ding, Functional mapping and cooperation between the cerebellum and cerebrum during word reading, Cerebr. Cortex 32 (22) (2022) 5175–5190.

[44] Y. Yum, S. Law, K. Mo, D. Lau, I. Su, M. Shum, Electrophysiological evidence of sublexical phonological access in character processing by L2 Chinese learners of L1 alphabetic scripts, Cognit. Affect Behav. Neurosci. 16 (2) (2016) 339–352, https://doi.org/10.3758/s13415-015-0394-z.

[45] L. Shen, X. Li, S. Huang, Y. Huang, X. Gao, Z. You, X. Tang, Comprehending scientific metaphors in the bilingual brain: evidence from event-related potentials, Front. Psychol. 13 (2022), https://doi.org/10.3389/fpsyg.2022.1037525.

[46] G. Thierry, Y.J. Wu, Brain potentials reveal unconscious translation during foreign-language comprehension, in: Proceedings of the National Academy of Sciences, vol. 30, 2007. DOI: 10.1038/nrn2241.

[47] R. Gu, Y. Ge, Y. Jiang, Y.J. Luo, Anxiety and outcome evaluation: the good, the bad and the ambiguous, Biol. Psychol. 85 (2010) 200–206, https://doi.org/10.1016/j.biopsycho.2010.07.001.

[48] Y. Luo, T. Wu, L.S. Broster, C. Feng, D. Zhang, R. Gu, et al., The temporal course of the influence of anxiety on fairness considerations, Psychophysiology 51 (2014) 834–842, https://doi.org/10.1111/psyp.12235.

[49] L. Xia, R. Gu, D. Zhang, Y. Luo, Anxious individuals are impulsive decision-makers in the delay discounting task: an ERP study, Front. Behav. Neurosci. 11 (2017) 1–11, https://doi.org/10.3389/fnbeh.2017.00005.

[50] Y. Satio, E.K. Horwitz, T.J. Garza, Foreign language reading anxiety. [J], Mod. Lang. J. 83 (1999) 202–218, https://doi.org/10.1111/0026-7902.00016.

[51] M. Zoghi, An instrument for EFL reading anxiety: inventory construction and preliminary validation, The Journal of Asia TEFL 9 (1) (2012) 31–56.

[52] M. Zoghi, M. Alivandivafa, EFL reading anxiety inventory (EFLRAI): factorial validity and reliability, J. Psychoeduc. Assess. 32 (4) (2014) 318–329, https://doi.org/10.1177/0734282913513686.

[53] Y.Y. Zhu, English Reading Anxiety of Non-English Majors in Higher Vocational Colleges in China - A Case Study of Qingdao Harbor Vocational and Technical College, Shandong University of Science and Technology, 2012. Unpublished Doctoral dissertation.

[54] E.M. Kulsum, The Students' Reading Anxiety and Reading Strategies in EFL Learning (Unpublished Doctoral Dissertation), Universitas Pendidikan Indonesia, Indonesia, 2018.

[55] A.H. Soomro, I. Khan, M. Younus, Top down, bottom up and classroom reading anxiety and their effect on reading performance of undergraduate engineering students in Pakistan, J. Appl. Res. High Educ. (2019), https://doi.org/10.1108/JARHE-07-2018-0138.

[56] C.D. Spielberger, Current trends in theory and research on anxiety, in: C.D. Spielberger (Ed.), Anxiety: Current Trends in Theory and Research, vol. 1, Academic Press, New York, 1972, pp. 3–19, https://doi.org/10.1016/B978-0-12-657401-2.50008-3.

[57] M.B. Denckla, R.G. Rudel, Rapid 'automatized' naming (r.a.n.): dyslexia differentiated from other learning disabilities, Neuropsychologia 14 (4) (1976) 471–479, https://doi.org/10.1016/0028-3932(76)90075-0.

[58] Elizabeth S. Norton, Maryanne Wolf, Rapid automatized naming (RAN) and reading fluency: implications for understanding and treatment of reading disabilities, Annu. Rev. Psychol. 63 (1) (2012) 427–452, https://doi.org/10.1146/annurev-psych-120710-100431.

[59] A. Woodcock, A.J. Sheen, N.K. James, B. Wilkinson, D. Hofman, S. Bullus, H. Butterfield, Letters, J. Wound Care 7 (9) (1998) 438.

[60] Y. He, X. Liu, J. Hu, E.S. Nichols, C. Lu, L. Liu, Difference between children and adults in the print-speech coactivated network, Sci. Stud. Read. (2021) 1–16.

[61] L. Liu, R. Tao, D. Gao, T. Qi, Y. Gao, B. Dai, A Chinese Character Reading Test for College Students, Committee of Psychometrics (Chinese Psychology Society, 2013. Registration number: 20130301.

[62] C.C. Sun, P. Hendrix, Chinese Lexical Database, 2017, https://doi.org/10.3758/s13428-018-1038-3, version 2.0.

[63] A. Delorme, S. Makeig, EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics, J. Neurosci. Methods 134 (1) (2004) 9–21, https://doi.org/10.1016/j.jneumeth.2003.10.009.

[64] M. Plöchl, J.P. Ossandón, P. König, Combining EEG and eye tracking: identification, characterization, and correction of eye movement artifacts in electroencephalographic data, Front. Hum. Neurosci. 6 (5) (2012) 278, https://doi.org/10.3389/fnhum.2012.00278.

[65] Zhou Luping, Xiaocong, Yan, Enhanced N170 elicited by words in Chinese developmental dyslexia, Neuroreport (2018), https://doi.org/10.1097/WNR.0000000000001080.

[66] M. Kast, S. Elmer, L. Jancke, M. Meyer, ERP differences of pre-lexical processing between dyslexic and non-dyslexic children, Int. J. Psychophysiol. 77 (1) (2010) 59–69, https://doi.org/10.1016/j.ijpsycho.2010.04.003.

[67] V. Dwivedi, J. Selvanayagam, Effects of dispositional affect on the n400: language processing and socially situated context, Front. Psychol. 12 (2021) 566894, https://doi.org/10.3389/fpsyg.2021.566894.

[68] L. Cui, X. Dong, S. Zhang, ERP evidence for emotional sensitivity in social anxiety, J. Affect. Disord. (2020), https://doi.org/10.1016/j.jad.2020.09.111.

[69] C. Langlet, J.P. Hainaut, B. Bolmont, Moderate anxiety modifies the electromyographic activity of a forearm muscle during a time-reaction task in women, Neurosci. Lett. 643 (2017) 1–7, https://doi.org/10.1016/j.neulet.2017.02.024.

[70] C.P. Tomczyk, G. Shaver, T.N. Hunt, Does anxiety affect neuropsychological assessment in college athletes? J. Sport Rehabil. 29 (2) (2020) 238–242, https://doi.org/10.1123/jsr.2018-0123.

[71] H. Li, B. Yuan, Y.J. Luo, J. Liu, Reading anxiety modulates the functional connectivity of the reading-related network during adult reading, Brain Lang. 242 (2023) 105278, https://doi.org/10.1016/j.bandl.2023.105278.

[72] T. Alvi, C.D. Kouros, J. Lee, D. Fulford, B.A. Tabak, Social anxiety is negatively associated with the theory of mind and empathic accuracy, J. Abnorm. Psychol. 129 (1) (2020) 108–113, https://doi.org/10.1037/abn0000493.

[73] B. Gagl, F. Richlan, P. Ludersdorfer, J. Sassenhagen, C.J. Fiebach, The Lexical Categorization Model: A Computational Model of Left Ventral Occipito-Temporal Cortex Activation in Visual Word Recognition, Cold Spring Harbor Laboratory, 2016, https://doi.org/10.1101/085332.

[74] B.A. Shaywitz, S.E. Shaywitz, B.A. Blachman, K.R. Pugh, R.K. Fulbright, P. Skudlarski, et al., Development of left occipitotemporal systems for skilled reading in children after a phonologically- based intervention, Biol. Psychiatr. 55 (9) (2004) 926–933, https://doi.org/10.1016/j.biopsych.2003.12.019.

[75] T. Dijkstra, W.J.B. van Heuven, The architecture of the bilingual word recognition system: from identification to decision, Biling. Lang. Cognit. 5 (2002) 175–197, https://doi.org/10.1017/S1366728902003012.

[76] F. Cao, R. Tao, L. Liu, C.A. Perfetti, J.R. Booth, High proficiency in a second language is characterized by greater involvement of the first language network: evidence from Chinese learners of English, J. Cognit. Neurosci. 25 (10) (2013) 1649–1663, https://doi.org/10.1162/jocn_a_00414.

[77] A. Grant, J. Wittmeyer, P. Li, What do bilingual models tell us about the neurocognition of multiple languages?, in: Book: the Handbook of the Neuroscience of Multilingualism, 2019.

[78] J.F. Kroll, J.G. Van Hell, N. Tokowicz, D.W. Green, The Revised Hierarchical Model: a critical review and assessment, Biling. Lang. Cognit. 13 (2010) 373–381, https://doi.org/10.1017/S136672891000009X.

[79] S. Horie, T. Yamasaki, T. Okamoto, T. Nakashima, K. Ogata, S. Tobimatsu, Differential roles of spatial frequency on reading processes for ideograms and phonograms: a high-density ERP study, Neurosci. Res. 72 (1) (2012) 68–78, https://doi.org/10.1016/j.neures.2011.10.003.

[80] N.J. Savill, G. Thierry, Reading for sound with dyslexia: evidence for early orthographic and late phonological integration deficits, Brain Res. 1385 (2011) 192–205, https://doi.org/10.1016/j.brainres.2011.02.012.

[81] K.E. Waldie, G. Badzakova-Trajkov, V.K. Lim, I.J. Kirk, Lexical decision making in adults with dyslexia: an event-related potential study, Ilha Desterro J. Engl. Lang. Lit. Engl. Cult. Stud. 63 (2012) 37–68.

[82] S. Yang, X. Zhang, M. Jiang, Bilingual brains Learn to use L2 alliterations covertly like poets: brain ERP evidence, Front. Psychol. 12 (2021), https://doi.org/10.3389/fpsyg.2021.691846.

[83] K.K. Amora, A. Tretow, C. Verwimp, J. Tijms, P.H.T. Leppänen, V. Csépe, Typical and atypical development of visual expertise for print as indexed by the visual word N1 (N170w): a systematic review, Front. Neurosci. 16 (2022), https://doi.org/10.3389/fnins.2022.898800.

[84] L. Cohen, S. Dehaene, Specialization within the ventral stream: the case for the visual word form area, Neuroimage 22 (1) (2004) 466–476, https://doi.org/10.1016/j.neuroimage.2003.12.049.

[85] L. Mei, G. Xue, Z.L. Lu, C. Chen, M. Wei, Q. He, et al., Long-term experience with Chinese language shapes the fusiform asymmetry of English reading, Neuroimage 110 (2015) 3–10, https://doi.org/10.1016/j.neuroimage.2015.01.030.

[86] S. Dehaene, G. Le Clec'H, J.B. Poline, D. Le Bihan, L. Cohen, The visual word form area: a prelexical representation of visual words in the fusiform gyrus, Neuroreport 13 (2002) 321–325, https://doi.org/10.1097/00001756-200203040-00015.

[87] R. Gaillard, L. Naccache, P. Pinel, S. Clémenceau, E. Volle, D. Hasboun, S. Dupont, M. Baulac, S. Dehaene, C. Adam, L. Cohen, Direct intracranial, fMRI, and lesion evidence for the causal role of left inferotemporal cortex in reading, Neuron 50 (2) (2006) 191–204, https://doi.org/10.1016/j.neuron.2006.03.031.

[88] M.L. Seghier, F. Kherif, G. Josse, C.J. Price, Regional and hemispheric determinants of language laterality: implications for preoperative fMRI, Hum. Brain Mapp. 32 (2011) 1602–1614, https://doi.org/10.1002/hbm.21130.

[89] M. Vigneau, V. Beaucousin, P.Y. Herve, H. Duffau, F. Crivello, O. Houde, et al., Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing, Neuroimage 30 (4) (2006) 1414–1432, https://doi.org/10.1016/j.neuroimage.2005.11.002.

[90] J. Grainger, P.J. Holcomb, Watching the word go by: on the time-course of component processes in visual word recognition, Language and Linguistics Compass 3 (1) (2009) 128–156, https://doi.org/10.1111/j.1749-818x.2008.00121.x.

[91] M. Kutas, S. Hillyard, Reading senseless sentences: brain potentials reflect semantic incongruity, Science 207 (4427) (1980) 203–205, https://doi.org/10.1126/science.7350657.

[92] C.T. Chang, C.Y. Lee, C.J. Chou, J.L. Fuh, H.C. Wu, Predictability effect on N400 reflects the severity of reading comprehension deficits in aphasia, Neuropsychologia 81 (2016) 117–128, https://doi.org/10.1016/j.neuropsychologia.2015.12.002.

[93] A. Cummings, R. Eponien, Verbal and nonverbal semantic processing in children with developmental language impairment, Neuropsychologia 48 (1) (2010) 77–85, https://doi.org/10.1016/j.neuropsychologia.2009.08.012.

[94] Charlotte DiStefano, Damla Senturk, Spurling Jeste Shafali, ERP evidence of semantic processing in children with ASD, Developmental Cognitive Neuroscience 100640 (2019), https://doi.org/10.1016/j.dcn.2019.100640.

[95] E.M. Moreno, M. Kutas, Processing semantic anomalies in two languages: an electrophysiological exploration in both languages of Spanish English bilinguals, Cognit. Brain Res. 22 (2005) 205–220, https://doi.org/10.1016/j.cogbrainres.2004.08.010.

[96] D.W. Green, Mental control of the bilingual lexicon-semantic system, Biling. Lang. Cognit. 1 (1998) 67–81.

[97] F.f. Grosjean, Studying Bilinguals, Oxford University Press, Oxford, 2008, https://doi.org/10.1006/jpho.1999.0097.

[98] A. De Bruin, A. Roelofs, T. Dijkstra, I. Fitzpatrick, Domain-general inhibition areas of the brain are involved in language switching: fMRI evidence from trilingual speakers, Neuroimage 90 (2014) 348–359, https://doi.org/10.1016/j.neuroimage.2013.12.049.

[99] T.F. Guo, C. Liu, Chen, S. Li, Inhibition of non-target languages in multilingual word production: evidence from Uighur-Chinese-English trilinguals, Acta Psychol. 143 (2013) 277–283.

[100] P.G. Aaron, R.M. Joshi, R. Gooden, K.E. Bentum, Diagnosis and treatment of reading disabilities based on the component model of reading: an alternative to the discrepancy model of LD, J. Learn. Disabil. 41 (1) (2008) 67–84.

[101] J. Kissler, K. Bromberek-Dyzman, Mood induction differently affects early neural correlates of evaluative word processing in L1 and L2, Front. Psychol. 11 (2021), https://doi.org/10.3389/fpsyg.2020.588902.

[102] K. Nakamura, N. Hara, S. Kouider, Y. Takayama, R. Hanajima, K. Sakai, et al., Task-guided selection of the dual neural pathways for reading, Neuron 52 (3) (2006) 557–564.