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·Original Article·

Endogenous language control in Chinese-English switching: an event-related potentials study

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ABSTRACT

The neural basis of language switching, especially endogenous language control, remains largely unclear. We used a cue-stimulus paradigm and measured behavioral indices and scalp event-related potentials to investigate the endogenous control of switching between Chinese and English. In the experiment, unbalanced Chinese (L1) - English (L2) speakers named pictures in L1 or L2 according to an auditory cue presented 700 ms (cue-stimulus interval) before the picture onset. The reaction time (RT) was longer in the switch condition and the switch cost (difference of RTs between switch and repeat conditions) of L1 (L2→L1) was greater than L2 (L1→L2). P2 component elicited by the cue onset showed the neural switch cost of L1 at the frontocentral regions, with a leftward distribution, but not the switch cost of L2. The greater switch cost of L1 in behavioral responses and neural activity suggests that the frontocentral areas play an important role in endogenous language control, and switching back to the native language might require more endogenous control.

Keywords: language switching; frontocentral region; neural switch cost; P2

INTRODUCTION

Bilinguals switch flexibly between the native language (L1) and the second language (L2) during speech production. A common method to investigate the question of how they switch between languages is a language-switching paradigm, in which participants use the same (repeat) or different (switch) languages in two consecutive trials. Usually, the reaction time (RT) in the switch condition is longer than that in the repeat condition and the difference of RTs is called the "switch cost". This is explained by the inhibitory control model, which proposes that bilinguals inhibit one language to use the other[1].

Based on the inhibitory control model, Meuter and Allport[2] extended the inhibition hypothesis by integrating task-set inertia[3]. They proposed that the amount of inhibition depends on the relative language dominance: that inhibition of L1 (stronger task) is stronger than that of L2. Besides, the inhibition of the non-target language carries on to the next trial, therefore unequal strengths of inhibition of the two languages need unequal efforts to overcome the inhibition, leading to asymmetric switch costs. Asymmetric switch costs have been replicated in numerous language-switching studies[4-7]. In addition to language-switching studies, asymmetric switch costs have also been found in switching between tasks with different levels of difficulty. Waszak, Hommel, and Allport[8] reported asymmetric switch costs when switching between tasks using previously exposed and unexposed stimuli. The previously exposed stimuli made the task easier. They proposed that the asymmetric switch costs in their study were due to the relative task difficulty. Furthermore, these results suggested that switching between L1 and L2 might be similar to switching between tasks of unequal difficulty. Importantly, task-switching studies often distinguish between endogenous (top-down, intentional, voluntary processes) and exogenous (bottom-up, nonintentional, involuntary processes) control[9]. However, very few studies have distinguished between these two types of control during language switching[4, 6, 7]. Costa and Santesteban[4] found that the switch cost decreased as the interval between cue and stimulus increased in highly-proficient bilinguals, and Verhoef *et al.*[6] found that asymmetric switch costs became symmetric with enough preparation time in unbalanced bilinguals. These studies suggested a role of endogenous control during language switching.

In addition to the above behavioral results, Verhoef *et al.*[7] separated endogenous from exogenous control and measured scalp activity. The scalp activity after the cue showed early posterior negativity when switching to L2 and late anterior negativity when switching to L1 and L2, suggesting that the neural basis of endogenous language control depends on the direction of language switching.

As no study has investigated the neural basis of endogenous control when switching between alphabetic and logographic languages, and since many Chinese are trying to learn English (potential Chinese-English bilinguals), understanding the neural mechanism of language switching in Chinese-English bilinguals would benefit a large population.

Previous research has shown differences in processing alphabetic and logographic languages[10-13]. Besides, language-switching studies on the difference between Spanish-English and Chinese-English switching showed that the right dorsolateral prefrontal cortex is involved in the former[14] and the bilateral frontal area and left ACC (anterior cingulate area) are involved in the latter[5]. For these reasons, it would be valuable to investigate the neural basis of endogenous control during Chinese-English switching.

We used a cue-stimulus paradigm to investigate the neural basis of endogenous control in Chinese-English switching. Since a long-duration cue (e.g. 250 ms) might mix the neural responses of cue processing with those of target processing, and the auditory and visual systems may use separate attention mechanisms[15, 16] (though this remains controversial), an auditory stimulus of short duration served as the cue for language in this study, to minimize interference by the presence of the cue; the behavioral responses and cue-related event-related potentiats (ERPs) were measured. The target regions were: midline sites (frontal and parietal) due to their roles in task switching[17, 18] and frontocentral regions due to their roles in language switching.

PARTICIPANTS AND METHODS

Participants

Fifteen healthy males (22.2 ± 0.86 years) were enrolled in this study. All had normal or corrected-to-normal vision, did not have any history of brain damage, and did not take any medication. All participants signed consent forms before the experiments and were paid 20 Chinese Yuan per hour as compensation.

The native language of the participants was Chinese (L1) and the second language English (L2). They had begun to learn English at a mean age of 11.5 ± 1.41 years and passed the College English Test - level 4. None of them had been abroad and each had spent less than one hour per day learning English during the previous month. Participants also self-rated their language proficiency using a 5-point scale (1–'very nonproficient', 5– 'very proficient') in four aspects: listening, speaking, reading, and writing. *T*-tests showed that the participants were more proficient in Chinese than English in all four aspects (listening: Chinese 4.33, English 3.20, $t(14) = 4.80$, $P < 0.001$; speaking: Chinese 4.33, English 2.87, $t(14) = 8.88$, $P < 0.001$; reading: Chinese 4.33, English 3.47, $t(14) = 4.52$, $P < 0.001$; writing: Chinese 4.00, English 2.93, $t(14) = 5.17$, $P < 0.001$).

Stimuli

A 50-ms auditory signal served as the cue for the language *via* its presenting position (left ear for Chinese, right ear for English). The sound level of the cue was suprathreshold and none of the participants had problems hearing it clearly, according to oral reports. A total of 56 target pictures of common objects and animals were selected from the International Picture Naming Project database[19]. All of the stimuli had simple and common names in both Chinese and English. Furthermore, the names of the pictures were limited to 1–2 characters in Chinese and 3–7 letters in English. The stimuli were presented on a ViewSonic 6E display, 60 cm in front of the participant, resulting in a visual angle of 9° × 22.7°.

Procedures

A schematic of the experiment is shown in Figure 1. At the beginning of a trial, a black fixation cross appeared with a 50-ms auditory cue and was displayed for an additional 700 ms. A picture was then displayed for 250 ms and a white cross replaced it until the participant responded, allowing a maximum reaction time of 2 000 ms. The participants were instructed to press a button while naming the picture in Chinese or English according to the location of the auditory cue (left for Chinese, right for English) as quickly and accurately as possible. According to the sequence of languages, all trials were grouped into the following four conditions: L1-switch (L2→L1), L1-repeat (L1→L1), L2-switch (L1→L2), and L2-repeat (L2→L2). Each block contained 59 trials but the first 3 trials were excluded from data analysis and the sequence of the remaining 56 trials used a pseudo-random technique such that each of the four conditions had 14 trials. Each participant performed 5 blocks. Therefore, we applied a language (Chinese *versus* English) × trial type (switch *versus* repeat) design and 280 trials were collected (70 trials per condition for each participant).

Before the main experiment, each participant named each picture both in Chinese and English on paper without time pressure and was taught the correct name in the case of an error. In addition, based on prior correct naming, the participants practiced 2–3 blocks until the naming accuracy was >95%. Since the participants were unbalanced bilingual speakers, it was possible that the task difficulty of naming in L1 or L2 were different. Importantly, it has been shown that the relative task difficulty is important for asymmetric switch cost[8]. Therefore, we checked the relative task difficulty of naming in two languages by measuring behavioral responses as an index of task difficulty using a blocked design.

Data Analyses

For the behavioral responses, only correct trials were used for further data analysis. Trials were discarded if the response was incorrect or the reaction time was <450 ms or >1450 ms. Data of one subject were removed from analysis due to poor quality of EEG recordings.

The electroencephalogram (EEG) was recorded using the EGI System with a 128-channel electrode cap. During recording, the signal was digitized at 1 000 Hz with a band-pass of 0.1–50 Hz. The reference electrode was Cz and the impedance of each electrode was kept below 30 kΩ. Our ERP analysis was similar to that of Li *et al.*[20]. In particular, EEG data were filtered offline (0.1–45 Hz) and segmented using a window of −200 to 750 ms relative to the cue onset for cue-related ERPs. Trials were discarded if the behavioral response was incorrect or if the amplitude of an epoch was >100 μV. After excluding these epochs, the data were baseline-corrected using the 100-ms pre-cue-onset period. Single epochs for the L1-switch (L2→L1), L1-repeat (L1→L1), L2-switch (L1→L2), and L2-repeat (L2→L2)

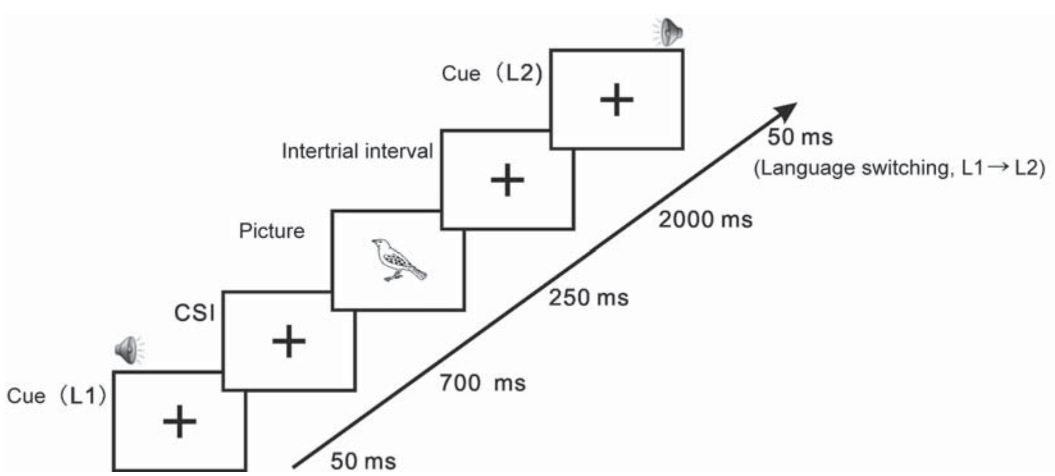

Fig. 1. Schematic of the experiment. The inter-trial interval of 2000 ms represents the maximum reaction time allowed. The second trial belongs to the L2 switch condition. CSI, cue-stimulus interval.

conditions were averaged to obtain cue-related ERPs.

For the ERP analyses, the midline and frontocentral electrodes Fz, FCz, Cz, Pz; FC3, FCz, and FC4 were selected as regions of interest. By visual inspection of cue-related ERPs, P2 component was selected for analysis and computed by averaging over ±20 ms of the mean P2 peak latency.

For the statistical analysis, we conducted repeated measures ANOVA on error rate, reaction times (RTs), and P2 responses. The ANOVA factors were trial type (switch *vs* repeat) and language (L1 *vs* L2). An additional factor, the electrode site (midline sites Fz, FCz, Cz, and Pz; frontocentral sites FC3, FCz, and FC4), was used in P2 analysis. For the ANOVA of P2 componets, the midline and frontocentral sites were analyzed separately. Furthermore, the neural switch cost for each language was analyzed using two-way (trial type × sites) repeated measures ANOVA to check the neural switching effect in each language. Follow-up analysis of activity at each site was conducted when the switch cost of a specific language was found in the midline or frontocentral sites. In addition, paired *t*-tests were run accordingly.

RESULTS

Behavioral Results

Two-way repeated measures ANOVA on error rate with trial type (switch *vs* repeat) × language (L1 *vs* L2) as main factors revealed a main effect of language [$F(1, 13) = 19.62$, $P < 0.01$], indicating that more errors were made when naming in L1 (5.5%) than in L2 (3.2%). No interactions among factors were found.

The mean RTs in all conditions with the standard error are shown in Figure 2. The ANOVA on RTs revealed a main effect of trial type [$F(1, 13) = 18.10$, $P < 0.01$], showing that RTs were longer in the switch condition than in the repeat condition for both L1 ($P < 0.05$) and L2 ($P = 0.061$). Interaction between trial type and language [$F(1, 13) = 8.94$, $P < 0.05$] indicated the asymmetric switch costs of L1 and L2. The switch cost (RT in the switch condition minus RT in the repeat condition) of L1 was 59 ms [paired *t*-test, $t(13) = 4.92$, $P < 0.001$] and that of L2 was 22 ms [paired *t*-test, $t(13) = 2.05$, $P = 0.061$]. The paired *t*-test showed no difference of RTs between L1 repeat and L2 repeat conditions [$t(13) = -0.199$, $P = 0.846$] and data from blocked-design experiment also did not show a language effect [$t(13) = -1.538$, $P = 0.148$]. These results indicated that the task difficulty of naming pictures in Chinese and in English did not differ.

As in previous studies, we also found a paradoxical language effect in the switch condition: the RT of L1 trials (848 ms) was longer than L2 (814 ms) [paired *t*-test, $t(13) = 2.41$, $P < 0.05$], but not in the repeat condition.

Since the spatial position-language set (left for Chinese, right for English) was fixed for all participants in the main experiment, we conducted a control experiment to check whether there is any specific combination of the left ear and Chinese, and the right ear and English. To run the control experiment, 15 participants of the same standard as the original group (6 males, 9 females) were recruited and instructed to perform the same task with a reversed set (left for English, right for Chinese). Combined with the data of the main experiment, we conducted mixed-design ANOVA using instruction, language, and trial type as variables. The data showed a main effect of trial type [$F(1, 27) = 26.99$, $P < 0.001$] and interaction between language and trial type [$F(1, 27) = 9.23$, $P < 0.01$], but no main effect of the instruction or interaction between instruction and the other two variables. In addition, after checking the control data alone, we found a main effect of trial type [$F(1, 14) = 9.23$, $P < 0.01$], that the mean RT in the switch condition (800 ms) was longer than that in the repeat condition (773 ms). We also found an interaction between trial type and language [$F(1, 14) = 4.88$, $P < 0.05$], indicating the asymmetric switch costs of Chinese and English. The switch cost of L1 was

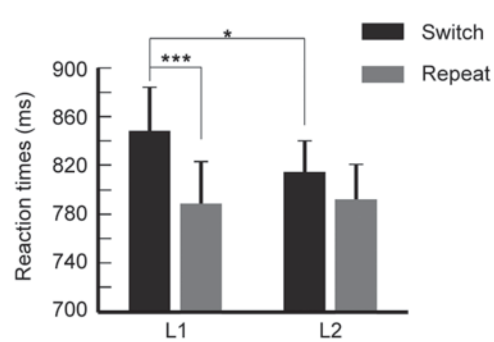

Fig. 2. Mean reaction times (RTs) across conditions with the standard error. RTs in the switch condition were longer than those of the repeat condition, and the switch cost of L1 was greater than that of L2. *P <0.05, ***P <0.001.

43 ms [paired *t*-test, $t(14) = 3.47$, $P < 0.01$] and that of L2 was 15 ms [paired *t*-test, $t(14) = 1.51$, $P = 0.155$]. Taken together, these results showed that the instruction is not a factor that would change the findings, suggesting that the left and right ear cues had no specific connection with Chinese and English.

We also ran another control experiment to check whether the cue-switching effect might be mixed with the language-switching effect. Eight participants (4 males, 4 females) named the pictures in Chinese and English in separate blocks regardless of cue position. The data did not show a cue-switching effect [$F(1, 7) = 0.31$, $P = 0.593$] for both L1 and L2, while the same participants showed a significant language-switching effect [$F(1, 7) = 19.34$, $P < 0.01$]. Therefore, we propose that the switching effect in the current study was mainly attributable to language.

Cue-related ERP Results

The grand averages of ERPs at the midline sites are shown in Figure 3.

P2 component (160–200 ms)

Midline sites The ANOVA showed main effects of site [$F(1,13) = 10.36$, $P < 0.001$] and trial type [$F(1,13) = 8.34$, $P < 0.05$], with P2 component being stronger in the switch condition (3.06 μV) than in the repeat condition (2.84 μV).

Two-way repeated measures ANOVA (trial type × site) for L1 and L2 was conducted to investigate the neural switching effect of each language in the midline sites. ANOVA for L1 trials showed a significant main effect of site [$F(3, 39) = 8.04$, $P < 0.001$] and a main effect of trial type [$F(1, 13) = 17.93$, $P < 0.01$]. Follow-up analyses for each site revealed significant effects of trial type at FCz [$F(1, 13) = 7.31$, $P < 0.05$] and Cz [$F(1, 13) = 10.82$, $P < 0.01$], indicating that the neural switch cost (activity in switch condition minus that in repeat condition) of L1 was represented at these sites. ANOVA for L2 trials only showed a significant main effect of site [$F(3, 39) = 11.59$, $P < 0.001$], but no effect of trial type.

Frontocentral sites Grand average ERPs at the bilateral frontocentral sites and the corresponding P2 components

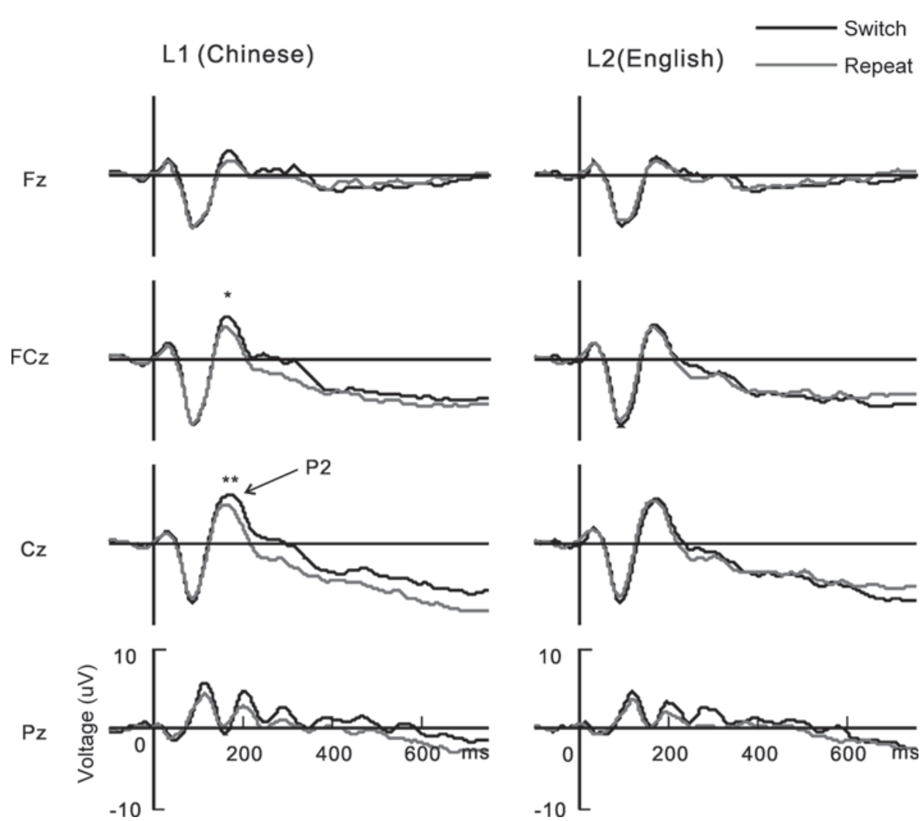

Fig. 3. Grand averages of cue-related ERPs at the midline sites. Zero on the horizontal axis represents the cue onset. ****P* **<0.05, *****P*** **<0.01.**

are shown in Figure 4. ANOVA showed interaction between site and language [$F(2, 26) = 3.76$, $P < 0.05$] and marginally significant interaction between language and trial type [$F(1, 13) = 4.52$, $P = 0.053$].

Two-way repeated measures ANOVA (trial type × site) for L1 and L2 was also conducted to investigate the neural switch cost of each language in these frontocentral sites. ANOVA for L1 trials showed a significant main effect of trial type [$F(1, 13) = 8.91$, $P < 0.05$] and follow-up analyses for each site revealed significant effects of trial type at FC3 [$F(1, 13) = 12.85$, $P < 0.01$] and FCz [$F(1, 13) = 7.31$, $P < 0.05$]. ANOVA for L2 trials did not show a neural switch cost at these frontocentral sites.

Similar to the RT analysis, we also conducted two-way repeated measures ANOVA (trial type × language) to check the asymmetric neural switch costs at the three sites (FCz, Cz, and FC3) where there was a significant effect of trial type. ANOVA at all of the three sites showed main effects of trial type [FCz: $F(1, 13) = 5.12$, $P < 0.05$; Cz: $F(1, 13) = 8.26$, $P < 0.05$; FC3: $F(1, 13) = 7.30$, $P < 0.05$], but only FC3 showed a significant interaction between trial type and language [$F(1, 13) = 5.37$, $P < 0.05$], indicating that the neural switch cost (P2 component in the switch condition minus that in the repeat condition) of L1 (1.33 μV) was greater than that of L2 (−0.04 μV). In addition, the P2 component at FC3 showed a main effect of language [$F(1, 13) = 14.14$, $P < 0.01$], with stronger responses in L1 trials (3.84 μV) than in L2 trials (2.95 μV). Moreover, the paired

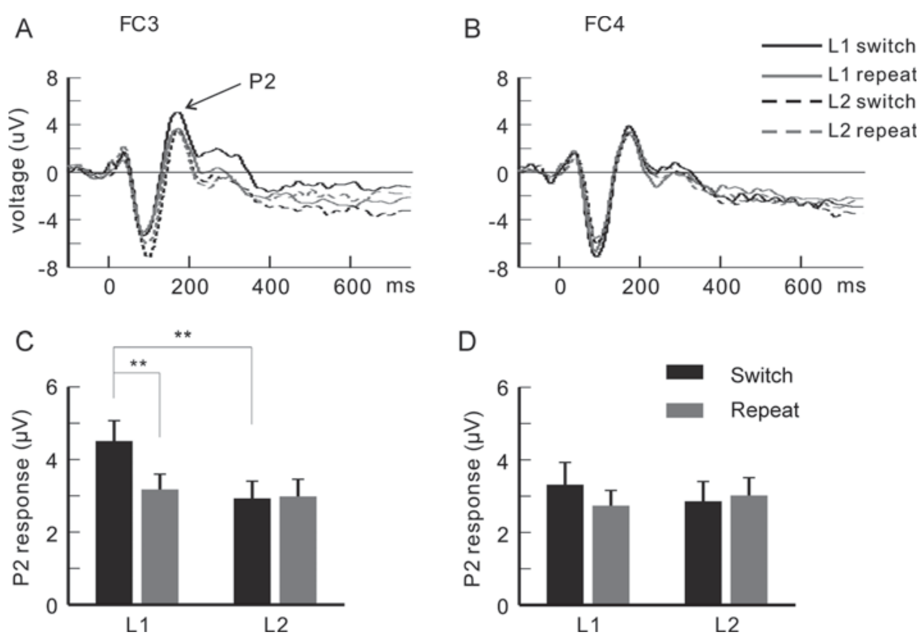

Fig. 4. Grand averages of cue-related ERPs at FC3 and FC4 (A and B) and P2 components at the corresponding sites and conditions (C and D). Zero in the horizontal axis represents the cue onset. Error bars represent standard error. **P <0.01.

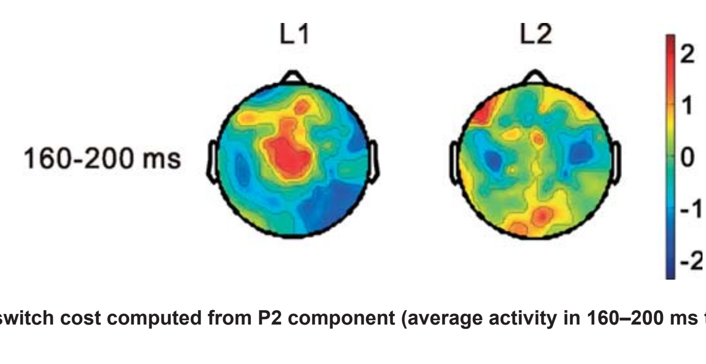

Fig. 5. Cortical topography of switch cost computed from P2 component (average activity in 160–200 ms time window) for L1 and L2.

t-test at FC3 showed a higher P2 component in the L1 switch condition (4.50 μV) than the L1 repeat condition (3.17 μV) [$t(13) = 3.59$, $P < 0.01$] and L2 switch condition (2.92 μV) [$t(13) = 3.73$, $P < 0.01$].

Taken together, P2 component showed the neural switching effect of L1 mainly at the frontocentral sites and a leftwards cortical distribution as shown in Fig. 5. In addition, asymmetric neural switch costs were only found at the left frontocentral region, suggesting that this region is more involved in the asymmetric switch costs found in the behavioral responses.

DISCUSSION

In the current study, we investigated the neural bases of endogenous language control when switching between Chinese and English in unbalanced Chinese-English bilinguals by measuring behavioral responses and cue-related ERPs. Our behavioral results were consistent with other studies, in that RTs were longer in the switch condition than in the repeat condition and the switch cost of L1 was greater than that of L2[2, 4-7]. Moreover, we found a higher error rate for L1 than for L2, confirming the findings from other studies with both balanced and unbalanced bilingual speakers[6, 7]. Similar to the behavioral responses, cue-related ERPs showed higher activity in the switch condition and a greater neural switch cost of L1 was found in the frontocentral regions.

In the present study, the neural switching effect appeared as early as ~180 ms after the cue onset (P2 component). Compared to the results of Verhoef *et al.*[7], who also investigated the neural bases of endogenous language control, the neural switch cost in our study appeared earlier. This might be due to the short duration of the auditory cue. Moreover, the cue-stimulus interval of 700 ms in the current study was longer than the sufficient preparation time of 600 ms for task switching[9] and has also been proposed to be optimal for language switching[6].

As in other studies[5, 14, 21-23], we found that the frontocentral regions were important for language switching. P2 component showed the neural switch cost of L1 at the frontocentral regions and further showed a left-shifted distribution. It was clear that the participants were more proficient in L1 than in L2 as shown by their language experience, however, the pictures for naming had common and simple names and the participants practiced until skillful in naming these pictures in both languages. By means of practice, the participants were able to name the pictures in Chinese and English without significant difference of RTs in the blocked design, suggesting that naming these pictures in Chinese and English had equal difficulty levels. Of course, naming the pictures in either language according to the cue could change the difficulty level. Yet, by matching difficulty levels in the blocked design, we excluded possible reason of asymmetric switch costs caused by unequal task difficulty levels.

Research on EEG alpha power has proposed that the left prefrontal cortex plays a greater role in approach behavior and the right prefrontal plays a greater role in inhibition[24-26]. Similarly, Lahat *et al.*[27] reported that Chinese-Canadian children showed a larger N2 component at left frontal sites in go-trials and at right frontal sites in no-go trials than European-Canadian children. Together with a previous EEG study, it has been suggested that the left frontal areas are important for effortful approach and the right frontal areas are important for effortful inhibition. Therefore, the left-shifted distribution of the neural switch cost of L1 in the present study might suggest that switching back to Chinese requires more effort.

Overall, unbalanced Chinese-English bilingual speakers showed the switching effect and a greater switch cost of L1 than that of L2 in both behavioral responses and cue-related neural responses. These results suggest that the frontocentral regions play an important role in endogenous language control. Furthermore, the leftwards cortical lateralization in the frontocentral region might suggest switching back to the native language requires more effort.

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