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# Dissociated stimulus and response conflict effect in the Stroop task: Evidence from evoked brain potentials and brain oscillations

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ABSTRACT

The Stroop task is a classic paradigm that can be used to examine cognitive control as it contains conditions with and without interference. Cumulative evidence suggests that both stimulus and response conflict contribute to the Stroop interference effect. However, it remains unclear whether there are dissociable event-related potential (ERP) or frequency band-specific electroencephalographic (EEG) power changes associated with stimulus conflict and response conflict. To investigate potential markers for each form of conflict, we applied a Stroop 2-1 mapping task in 20 healthy young adults. Results showed that a negative deflection in the 350–500 ms time window (N450) and a positive deflection in the 600–900 ms time window (late positive component, LPC) were associated with response conflict and stimulus conflict, respectively. Time-frequency analyses found that both stimulus and response conflict induced theta band power changes and that response conflict additionally induced a beta band power change. These results indicate that stimulus and response conflict in the Stroop task are associated with different ERP effects and brain oscillatory features.



## 1. Introduction

Cognitive control refers to the ability to shape thoughts and behaviors flexibly to accomplish internal goals (Miller & Cohen, 2001). The Stroop task is one of the classic tasks used to measure this flexibility (Stroop, 1935). Specifically, compared with congruent trials, in which color words are printed in the corresponding color ink, incongruent trials, in which the same color words are printed in a non-matching color, have increased reaction times and error rates during color naming or word reading (MacLeod, 1991).

Earlier theories proposed that this interference is caused by stimulus conflict (Hock & Egeth, 1970) or response conflict (Dyer, 1973; Posner & Snyder, 1975). Stimulus conflict refers to inconsistencies between ink color and word meaning, whereas response conflict refers to competition among different response possibilities (van Veen & Carter, 2005). Cumulative evidence now suggests that the interference is caused by both stimulus- and response-level conflict (Caldas, Machado-Pinheiro, Souza, Motta-Ribeiro, & David, 2012; Chen, Bailey, Tiernan, & West, 2011; De Houwer, 2003; Kim, Kroger, & Kim, 2011; MacLeod, 1991; Szucs & Soltesz, 2010, 2012; van Veen & Carter, 2005; West, 2003).

To capture the fast processing of conflict a high temporal resolution technique, event-related potentials (ERP), was used in literature. Previous ERP studies have revealed that incongruent trials evoke larger amplitudes in a 350–500 ms time window and a 600–900 ms time window compared with congruent trials (Liotti, Woldorff, Perez, & Mayberg, 2000; West, 2003). The former interval represents a negative deflection, termed the N450 (West, 2003), whereas the latter interval represents a positive deflection, termed the late positive component (LPC). However, it is still controversial whether these deflections correspond to stimulus or response conflict. In particular, the N450 has been associated with stimulus conflict (Caldas et al., 2012; Coderre, Conklin, & van Heuven, 2011; Szucs & Soltesz, 2012), response conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Chen et al., 2011) and in some cases both stimulus and response conflict (Markela-Lerenc et al., 2004; Szucs & Soltesz, 2010). Similarly, the LPC has been associated with stimulus conflict (Li, Wang, Duan, & Zhu, 2013), response conflict (Donohue, Liotti, Perez, & Woldorff, 2012; Liotti et al., 2000; van

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Veen & Carter, 2005; West & Alain, 2000; West, 2003) and both types of conflict (Chen et al., 2011; West, Jakubek, Wymbs, Perry, & Moore, 2005).

Previous studies have also investigated the time course of response activation in the Stroop task using the lateralized readiness potential (LRP) (Lansbergen & Kenemans, 2008; Szucs & Soltesz, 2007, 2008, 2010, 2012; Szucs, Soltesz, Bryce, & Whitebread, 2009; Szucs, Soltesz, & White, 2009). The LRP indicates increased EEG negativity over the motor cortex contralateral to a planned motor response (Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Luck, 2005). While previous studies have found inconsistent results in the classic Stroop task (Lansbergen & Kenemans, 2008; Szucs & Soltesz, 2007; Szucs, Soltesz, Bryce, et al., 2009), it remains unclear whether the stimulus and response conflict engage LRP differently. Therefore, the primary aim of the present study was to isolate the specific effects of stimulus and response conflict.

To dissociate the effects of stimulus and response conflict effectively, it is necessary to employ a design wherein the two forms of conflict can be experimentally separated from each other. In a previous study, we used both explicit and implicit Stroop tasks to isolate stimulus and response conflict-related neural deflection (Li et al., 2013). In the experiment, participants were asked to make a color judgment (explicit task) or a rotation judgment (implicit task) on color words. It was hypothesized that both stimulus and response conflict would be engaged in the color judgment, whereas only stimulus conflict would be involved in the rotation judgment because the rotation did not depend on word meaning or color. Consistent with the prediction, we found LPC in both judgments. However, N450 was only found in the color judgment. Because only stimulus conflict exists in the rotation judgment, LPC was linked with stimulus conflict processing, and the N450 was attributed to response conflict processing.

One issue of concern in the Li et al. study is that the response terminated the stimulus presentation. While this was not uncommon in previous studies (Chen et al., 2011; De Houwer, 2003; West et al., 2005), the stimulus conflict-related LPC effect may be partly explained by a varied response time (RT) distribution, such that longer stimulus duration enhanced the stimulus conflict effect. Various strategies have been used to address the duration issue. For instance, the stimulus duration has been set as 150 ms, 250 ms, or 300 ms (Donohue et al., 2012; Liotti et al., 2000; West, 2003), durations far shorter than the mean RT. The short duration, however, may additionally overload the working memory's capacity to maintain or retrieve the stimulus feature before the response can be executed. In other studies, the stimulus was presented with a fixed duration (e.g., 1000 ms) (Coderre et al., 2011; Hanslmayr et al., 2008). The long fixed duration provided constant physical input and may thus have avoided the above-mentioned confounding effects.

Another approach is the Stroop 2-1 mapping paradigm (De Houwer, 2003), which has been successfully used in fMRI studies to dissociate the two forms of conflict in the Stroop task (Kim et al., 2011; van Veen & Carter, 2005). In this paradigm, two colors are associated with each response hand. This manipulation allows stimuli to be congruent (CON; word and color are the same), incongruent at only the stimulus level (SI; word and color are different but mapped onto the same response hand), or incongruent at both the stimulus and response levels (RI; word and color are different and mapped onto opposite response hands). In the 2-1 mapping task, it has been found that response conflict and stimulus conflict effects are associated with different sub-regions in both the dorsolateral prefrontal cortex (DLPFC) and the anterior cingulate cortex (ACC) (van Veen & Carter, 2005). Moreover, response conflict activates the superior temporal cortex and the thalamus (van Veen & Carter, 2005). Similarly, Kim et al. (2011) found dissociated effects in the ACC, such that the caudal dorsal ACC was involved in stimulus conflict and the rostral dorsal ACC was involved in response conflict. These results suggest that the 2-1 mapping task can be used to reveal the specific neural effects of stimulus and response conflict.

In one ERP study that employed the Stroop 2-1 mapping task (Chen et al., 2011), the N450 was associated with response conflict, whereas the LPC was associated with both stimulus and response conflict. However, these effects were calculated using specific electrodes. Electrode-wise analyses may be appropriate in a confirmatory study. As the present study's exploration used a design that has rarely been used in ERP studies, a data-driven approach might be more appropriate (Wang, Zhu, & Bastiaansen, 2012). One such approach is cluster-based random permutation testing (Maris & Oostenveld, 2007; Nichols & Holmes, 2002). This statistical procedure optimally handles the multiple comparisons problem inherent in the use of a large number of electrodes to examine cognitive process-related ERP effects while simultaneously retaining reasonable statistical power. It naturally addresses interactions among time points, electrodes, and frequency bins by identifying clusters of significant differences between conditions in multiple (e.g., time, space and frequency) dimensions (see Section 2 for more detail).

In addition to ERP analyses, time-frequency (TF) analyses of the electroencephalogram (EEG) have been performed (Brittain et al., 2012; Hanslmayr et al., 2008; Tang, Hu, Li, Zhang, & Chen, 2013). While traditional ERP analyses mainly focus on evoked brain potentials (Luck, 2005), TF analyses mainly examine induced brain signals (Makeig, Debener, Onton, & Delorme, 2004). Thus the TF analyses are complementary to the ERP analyses.

In the Stroop task, power changes in the theta band are associated with conflict processes, and recent studies have shown that incongruent trials enhance theta power more than congruent trials do (Brittain et al., 2012; Hanslmayr et al., 2008; Tang, Hu, & Chen, 2013). This theta power change was associated with both stimulus and response conflict in the Flanker task (Nigbur, Cohen, Ridderinkhof, & Stürmer, 2012) and a task that combined a Simon and Stroop task (Wang, Li, Zheng, Wang, & Liu, 2014). The enhanced theta effect was distributed in frontal regions and may be generated from medial frontal cortex (MFC) or ACC (Cavanagh, Cohen, & Allen, 2009; Cavanagh et al., 2011; Hanslmayr et al., 2008; Nigbur, Ivanova, & Sturmer, 2011; Nigbur et al., 2012). The increased theta power change when either stimulus or response conflict occurs may be related to enhanced cognitive control (Cavanagh et al., 2009, 2011; Hanslmayr et al., 2008; Nigbur et al., 2011, 2012; van Steenbergen, Band, & Hommel, 2012).

Beta band power change was associated with conflict processing in an intracranial recording study (Brittain et al., 2012) and a scalp recording study (Wang et al., 2014). Wang et al. found a reduced beta band (13–20 Hz) power change at approximately the 400 ms time window in the stimulus-response conflict condition compared with the power change of the stimulus–stimulus conflict condition in a combined Simon and Stroop task. It was suggested that the suppressed effect of the beta band most likely reflected top-down inhibition of proponent responses (Liang et al., 2014). It has also been suggested that this power change in the beta band is associated with response preparation (Miller et al., 2007; Pfurtscheller, Graimann, Huggins, Levine, & Schuh, 2003). However, it remains unclear whether the effect of the stimulus conflict is dissociable from that of the response conflict in the above-mentioned band-specific power changes.

The present study employed the Stroop 2-1 mapping task to disentangle the stimulus and response conflict in terms of ERP effects and brain oscillation features. Following the 2-1 mapping design logic, indices selective for stimulus conflict were expected to display greater amplitudes for the SI and RI than for the CON but no difference between the SI and RI. Indices selective for response conflict should display similar amplitudes in the CON and SI conditions, and the amplitudes should be increased only in the RI condition.

Finally, indices involved in general conflict (i.e., conflict regardless of nature or source) should display increases in amplitude in response to the SI and RI conditions compared with the CON condition.

## 2. Methods

### 2.1. Participants

Twenty healthy native Chinese speakers participated in the experiment (12 female, 8 male; age range 19–26 years; mean age 23 years). All were right-handed with normal or corrected-to-normal vision, and none showed neurological impairment. All participants signed a written informed consent form approved by the local ethics committee.

### 2.2. Stimuli

In the Stroop task, four color words ("green," "yellow," "red," and "blue") were printed in their corresponding color ink or in one of the non-matching colors (e.g., the word "red" was printed in yellow). Two colors were associated with each response hand (i.e., red and yellow for the left hand, blue and green for the right hand). This manipulation allowed the stimuli to be congruent (CON; word and color are the same, e.g., "red" in red ink), incongruent at only the stimulus level (SI; word and color are different but mapped onto the same response hand, e.g., "red" in yellow ink), or incongruent at both the stimulus and response levels (RI; word and color are different and mapped onto opposite response hands, e.g., "red" in green ink). In each condition there were 144 items.

### 2.3. Procedure

In each trial, a fixation cross was presented for 500 ms, followed by a 200 ms blank. A centralized color word was presented 1000 ms after the blank in SONG style (size = 40). Then a blank was presented for a duration randomly selected between 850 ms and 1350 ms. Participants were asked to indicate the word color by pressing the left (for red and yellow) or right (for blue and green) buttons as soon and accurately as possible when the stimulus was presented. The color-button correspondence was counterbalanced across participants. All stimuli were pseudo-randomly presented. Before the experiment, the participants were required to perform at least 12 correct trials in 16 practice trials.

### 2.4. Data collection

The EEG data were collected from a 32 standard channel (10/20 system) cap (Fp1, Fp2, F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, F7, FT7, F8, FT8, CP3, CPz, CP4, TP7, P7, TP8, P8, P3, Pz, P4, O1, Oz, and O2; Brain Products, Munich, Germany), in addition to the three electrodes used to measure eye movement. The EEG was continuously recorded using a 0.016 Hz high-pass (time constant is 10 s) and 125 Hz low-pass filter sampled at 500 Hz. EEG responses were referenced to the left mastoid online. All of the electrode impedances were kept below 5 kΩ during the recording.

### 2.5. ERP analyses

The EEG data were re-referenced offline to the average of the two mastoids, and the eye blink effect was removed using the Brain Vision Analyzer software (version 1.0). The data were then transferred into the Fieldtrip software package, which is an open-source Matlab toolbox for neurophysiological data analyses (Oostenveld, Fries, Maris, & Schoffelen, 2011). The data were filtered with a 0.016–30 Hz bandpass. For stimulus-locked analyses, the critical epochs ranged from −200 ms to 1000 ms relative to the onset of the stimulus, with −200 ms to 0 ms serving as the baseline. For response-locked analyses, the data were segmented from −1100 ms to 500 ms relative to the response onset, and the baseline was from −800 ms to −600 ms. After artifact rejection (±80 μV), each condition had more than 100 trials for the stimulus-locked results and 90 trials for the response-locked results for each participant. To quantify ERP differences among conditions, two time windows (i.e., 350–500 ms and 600–900 ms) were selected based on previous studies (Chen et al., 2011; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004). The amplitude values within these two time windows were averaged for each condition, each electrode and each subject.

### 2.6. LRP analyses

Following convention, we adopted C3 and C4 in the 10/20 electrode system to compute the LRP. The formula for computation was $[(C4-C3)_{\text{left hand response}}+(C3-C4)_{\text{right hand response}}]/2$ (Coles, 1989; Gratton et al., 1988) for both stimulus- and response-locked LRP. Because the accuracy was high in each condition (see Section 3), we analyzed only the correct trials.

### 2.7. TF analyses

The preprocessing steps were the same as those used in the ERP analyses, except for the following parameters. The low-pass filter was set at 100 Hz. To catch low-frequency power changes, the time epochs ranged from −1000 to 2000 ms relative to stimulus onset in the stimulus-locked analyses and ranged from −1500 ms to 1500 ms relative to the response onset in the response-locked analyses. Because long time epochs were used, the artifact rejection criteria were set to ±150 μV, resulting in more than 85 trials for each condition for each participant. The methods for the TF analyses were the same as those used in a previous study (Wang et al., 2012). As we analyzed TF data within the low-frequency range (2–30 Hz), a 400 ms Hanning window was used to compute power changes in frequency steps of 1 Hz and time steps of 10 ms.

In the present study, to limit the number of comparisons, we focused on power changes in the theta and beta bands. The partition of the frequency-band followed previous studies. The theta band was segmented from 4 Hz to 7 Hz (Engel & Fries, 2010; Hanslmayr et al., 2008; Nigbur et al., 2011), while the beta band was segmented from 13 Hz to 30 Hz (Engel & Fries, 2010; Hanslmayr et al., 2008). After acquiring the TF representations of single trials, we averaged the power estimates over trials for each subject, each condition and within theta, low beta and high beta frequency bands. We averaged the beta power change within each frequency band for both low beta (13–20 Hz) and high beta (20–30 Hz) based on the maps of individual condition pattern and condition comparisons. The resulting subject-averaged power changes in the post-stimulus interval were expressed as a relative change from the baseline interval (from −500 to −150 ms relative to the stimulus onset in the stimulus-locked analyses and from −950 to −600 ms relative to the response onset in the response-locked analyses). The baseline for stimulus-locked TF analyses was consistent with a previous study (Wang et al., 2012), and the baseline for response-locked TF analyses was consistent with the setting in response-locked ERP analyses.

### 2.8. Statistical analyses

We used a cluster-based random permutation test (Maris & Oostenveld, 2007) to test the study's hypotheses. For every data point (electrode by time for the ERP data, electrode by time by frequency for the TF data) of the two conditions, a simple dependent-sample *t*-test was performed (giving uncorrected *p*-values). To enhance the statistical power, we averaged the pre-selected frequency and time windows for each electrode in the TF analyses. This selection was based on consistent patterns across three conditions as well as comparisons among conditions, with details in Section 3. Then, all adjacent data points exceeding a preset significance level (5%) were grouped into clusters. For each cluster, the sum of the *t*-statistics was used in the cluster-level test statistic. Next, a null distribution, which assumes no difference between conditions, was created. This distribution was obtained by creating 1000 permutations of the random assignment of conditions within subjects and calculating the largest cluster-level statistic for each randomization. Finally, the actual observed cluster-level test statistics were compared against the null distribution, and clusters falling in the highest or lowest 2.5 percentiles were considered significant. Moreover, to increase the stability of the TF results, we followed a previous study (Tang, Hu, & Chen, 2013) by reporting clusters that lasted for at least 0.25 s.

## 3. Results

### 3.1. Behavioral results

A one-way repeated-measures analysis of variance (ANOVA) was performed for our behavioral data analysis. There was a significant main effect of conflict on accuracy [Mean ± SD, CON, 97.7 ± 1.7%; SI, 98.5 ± 1.3%; RI, 95.7 ± 3.5%; $F(2, 38) = 12.78$, $p = 0.001$], with lower accuracy in the RI than in the SI ($p = 0.002$) and CON ($p = 0.014$) and lower accuracy in the CON than in the SI ($p = 0.040$). There was also a significant main effect of conflict on RT [CON, 470 ± 76 ms; SI, 474 ± 83 ms; RI, 502 ± 88 ms; $F(2, 38) = 29.969$, $p < 0.001$], with longer RT in the RI than in the SI and CON ($ps < 0.001$), but there was no significant RT difference between the CON and SI.

### 3.2. Stimulus-locked ERP results

Fig. 1 presents the time course and topography of the stimulus-locked ERP. As the significant clusters were slightly different between the N450 and LPC time windows, we present the frontal-central electrodes (F3, Fz, F4, C3, Cz, C4) to represent the condition differences across time windows. In the 350–500 ms time window,

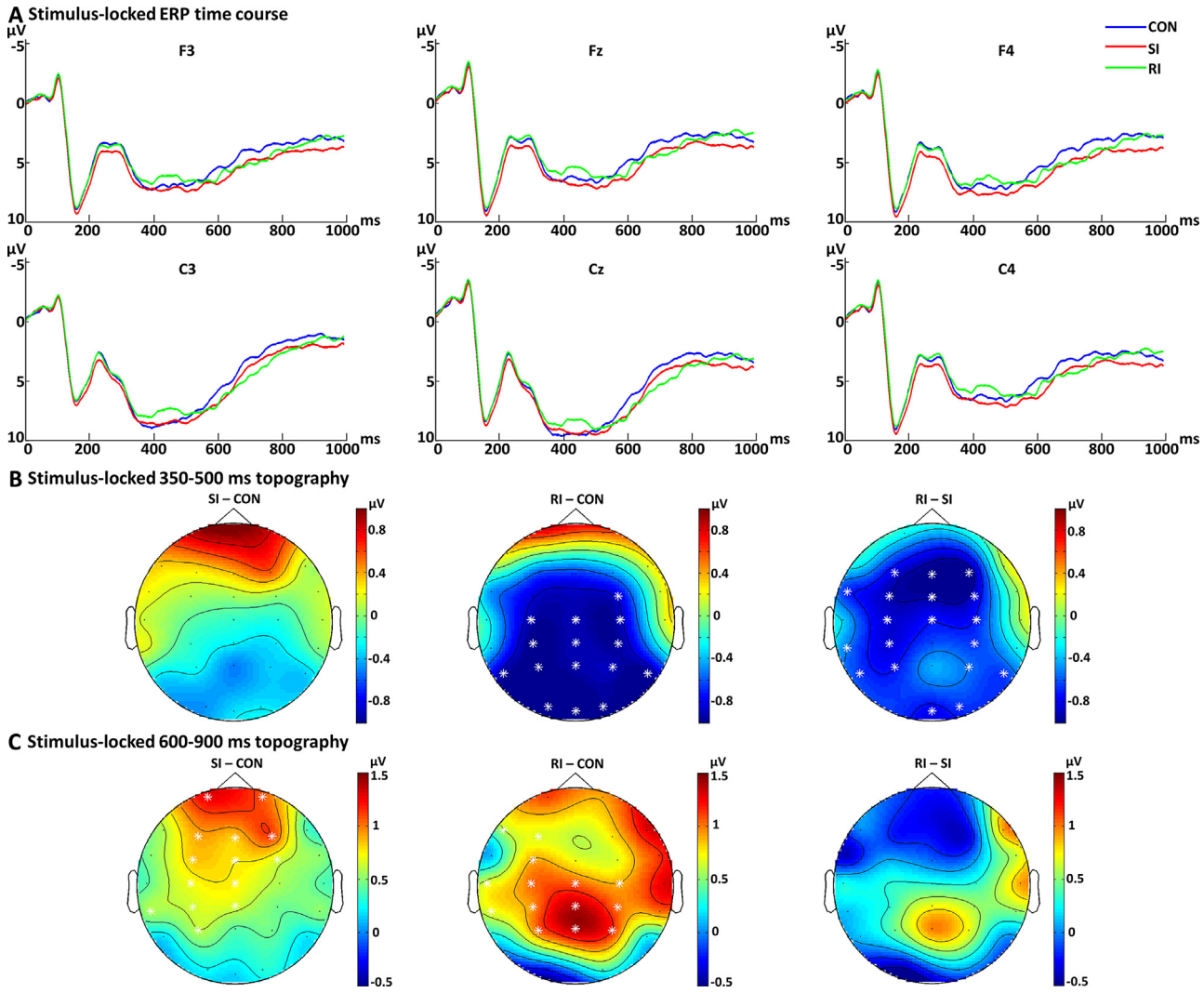


**Fig. 1.** Stimulus-locked ERP effect. (A) ERP time course in the frontal-central electrodes (F3, Fz, F4, C3, Cz, C4). (B) Topography of the condition differences in the 350–500 ms time window. Significant clustering was found in RI-SI and RI-CON. (C) Topography of the condition differences in the 600–900 ms time window. Significant clustering was found in SI-CON and RI-CON.
Note: * Indicates an electrode showing a significant condition effect. CON: congruent trial; SI: stimulus incongruent trial; RI: response incongruent trial.

a significant effect of conflict on the N450 was found across conditions, with larger negative deflection in the RI than in the SI ($p = 0.001$) and CON ($p = 0.003$), whereas no difference was found between the SI and CON. The amplitude pattern suggested that the N450 effect was associated with response conflict. In the 600–900 ms time window, the positive deflection in both the RI ($p = 0.005$) and SI ($p = 0.005$) was larger than that in the CON, whereas no difference was found between the RI and SI. This amplitude pattern suggested that the LPC effect was specifically associated with stimulus conflict.

### 3.3. Response-locked ERP results

Fig. 2 presents the time course and topography of the response-locked ERP. In the 350–100 ms time window before response onset, the amplitude in the RI was significantly more negative compared with that in the SI ($p = 0.032$), but there were no amplitude differences between the RI and CON or between the SI and CON. In the 0–100 ms time window after the response, the amplitude in the RI was significantly more negative than that in the SI ($p = 0.003$) and CON ($p = 0.037$), but there were no differences between the SI and CON. In the 100–300 ms time window after the response, the amplitude in the SI was larger than that in the CON ($p = 0.018$), while the difference between the CON and RI showed a trend toward significance ($p = 0.055$).

### 3.4. LRP results

Fig. 3 presents the LRP results. The results revealed a larger negative LRP amplitude in the RI compared with the CON ($p = 0.005$) and SI ($p = 0.026$) during the 500–700 ms after the stimulus onset in the stimulus-locked analyses. The significant effect in amplitude was only detected in the RI, and it was more negative than in the SI ($p = 0.007$) from −120 ms to the response onset in the response-locked analyses.

### 3.5. Stimulus-locked TF results

Fig. 4 presents stimulus-locked TF results. Based on condition contrast maps and TF representations in each individual condition, we statistically tested two clusters in theta band (200–600 ms and 600–1000 ms) and two clusters in beta band (0–500 ms and 600–1000 ms) in stimulus-locked analyses. Stimulus and response conflict effects were separated in the theta band (4–7 Hz). During

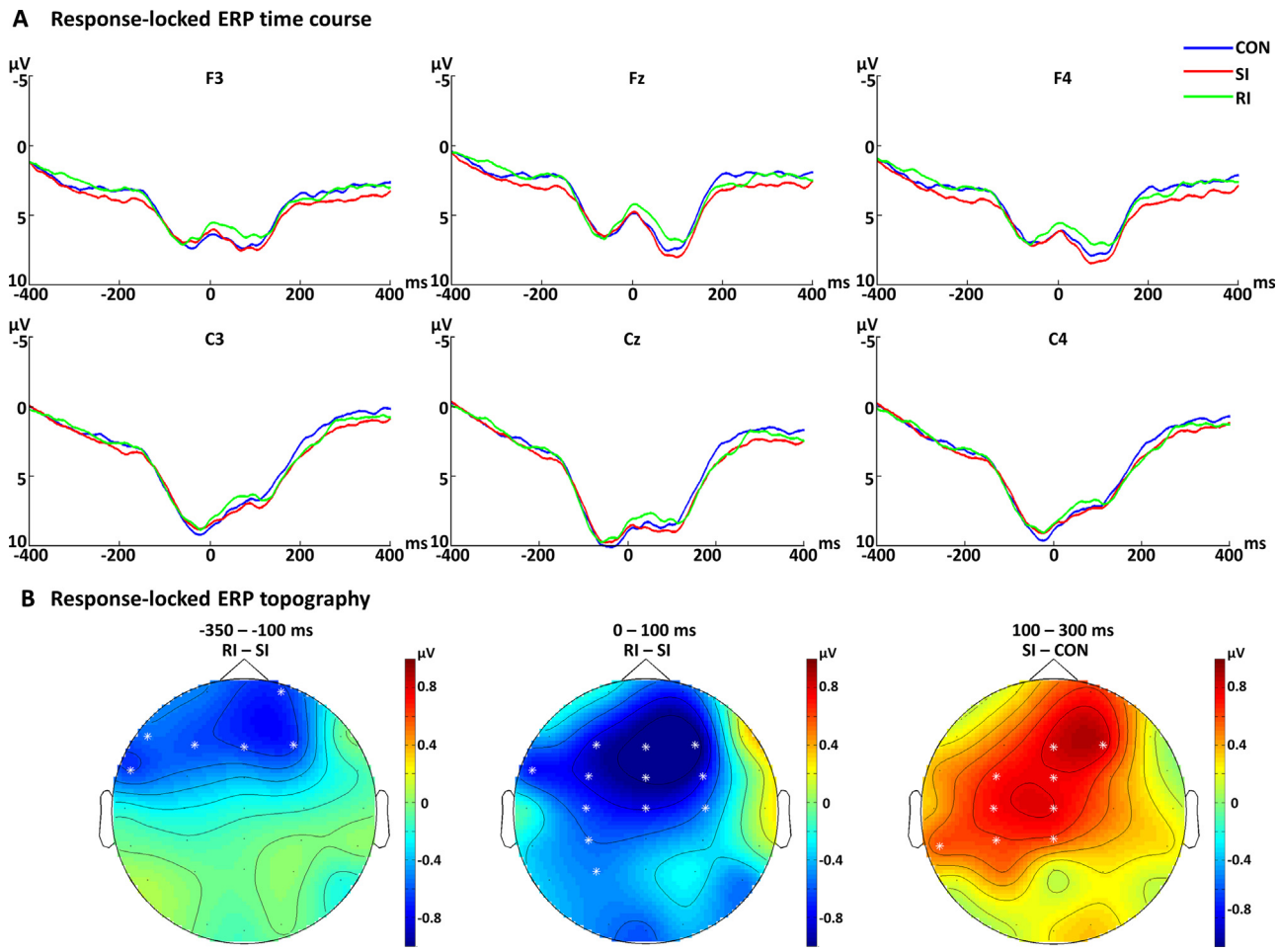


**Fig. 2.** Response-locked ERP effect. (A) ERP time course in the frontal-central electrodes (F3, Fz, F4, C3, Cz, C4). (B) Topography of condition differences. Note: * Indicates an electrode showing a significant condition effect. CON: congruent trial; SI: stimulus incongruent trial; RI: response incongruent trial.

an earlier time window (200–600 ms) there was significantly stronger power in the RI compared to the SI ($p < 0.001$) and CON ($p = 0.001$). However, in a later time window (600–1000 ms), the theta power change in the SI was stronger than that in the CON ($p = 0.009$), and the power change in the RI tended to be larger than that in the CON ($p = 0.055$). No difference in power change was found between the SI and RI. The results in the theta band were consistent with the ERP results, suggesting that response and stimulus conflict may occur in different time windows. In the beta band (13–20 Hz), the power in the 600–1000 ms time window decreased significantly more in the RI compared with the SI ($p = 0.002$).

### 3.6. Response-locked TF results

Fig. 5 presents the response-locked TF results. Based on condition contrast maps and TF representations in each condition, we statistically tested one cluster in the theta band (−200 to 100 ms) and one cluster in the beta band (0–300 ms) in response-locked analyses. In the response-locked analyses, there were response conflict effects in both the theta and beta bands. The power in the theta band increased more in the RI than it did in the SI ($p < 0.001$) and CON ($p = 0.021$), from −200 to 100 ms relative to the response onset. The power in the beta band was lower in the RI than it was in the SI ($p = 0.002$) in the 0–300 ms time window after the response onset.

## 4. Discussion

By employing the Stroop 2-1 mapping task, the present study aimed to dissociate stimulus and response conflict effects in terms of ERP effects and TF representations. ERP data showed that the two types of conflict effects were distinguishable in terms of N450 and LPC effects and LRP results. TF representations also showed that the two types of conflict could be distinguished in terms of power change in the theta and beta bands. The results suggest that stimulus conflict and response conflict in the Stroop task are dissociable.

### 4.1. ERP results

In the Stroop task, N450 and LPC were associated with conflict processes. However, as reviewed in the Introduction, whether ERP effects are specific to stimulus or response conflict is unclear based on earlier research. Our first aim was therefore to experimentally dissociate stimulus and response conflict-related ERP effects by employing the Stroop 2-1 mapping task. Using this task we were able to create a condition that only included stimulus conflict by mapping two colors onto one button, thus providing an opportunity to isolate stimulus and response conflict. In particular, ERP effects sensitive to stimulus conflict should demonstrate differences between the SI and CON and between the RI and CON. In parallel, ERP effects sensitive to response conflict should demonstrate differences between the RI and SI and between the RI and

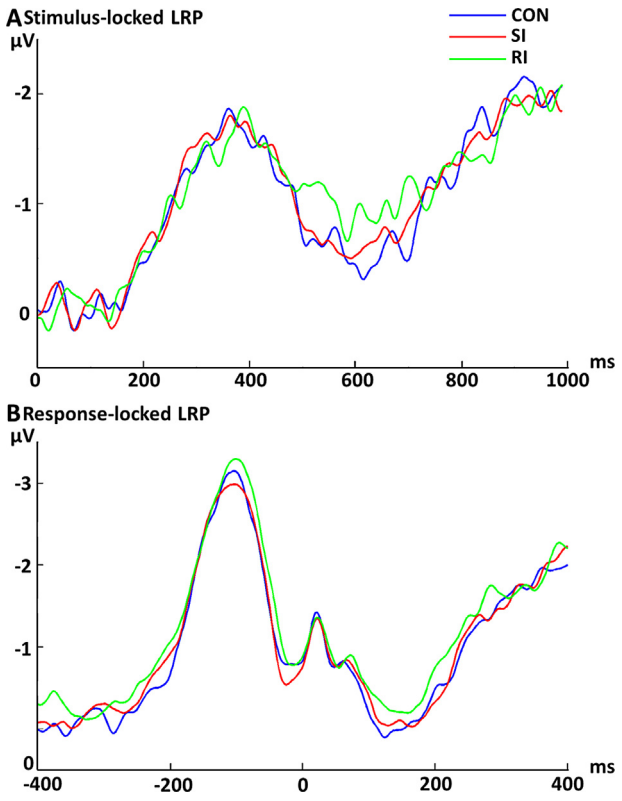


**Fig. 3.** Time course of the LRP effect for (A) stimulus-locked analyses and (B) response-locked analyses.
Note. CON: congruent trial; SI: stimulus incongruent trial; RI: response incongruent trial.

CON. Our findings exactly matched these predictions. The N450 amplitudes were increased from the CON to RI and from the SI to RI, whereas LPC amplitudes were increased from the CON to both the SI and RI in stimulus-locked analyses. Response-locked analyses also showed a response conflict effect around response onset and a stimulus conflict effect after response completion. Because the mean RT was approximately 470 ms across three conditions, the time window of these effects further mirrored the stimulus-locked N450 and LPC effect. These results suggest that the N450 and LPC effects were associated with response and stimulus conflict, respectively.

This association between N450 and response conflict was in line with recent findings (Botvinick et al., 2001; Chen et al., 2011; Tillman & Wiens, 2011). For instance, Tillman and Wiens (2011) manipulated the proportion of incongruent trials in total trials (20% vs. 80%) and hypothesized that response conflict would be greater when incongruent trials were rare compared to when incongruent trials were frequent because participants adapt to the conflict of frequent incongruent trials. Consistently, the N450 effects were significantly larger when the incongruent trials were rare than when the trials were frequent. Importantly, by employing the Stroop 2-1 mapping task, Chen et al. (2011) found an association between N450 effects and response conflict. The association between N450 and response conflict was also consistent with our recent observation that N450 was absent when response conflict was removed from the task design (Li et al., 2013).

The LPC effect was associated with stimulus conflict, consistent with our recent study (Li et al., 2013) in which participants were asked to judge the rotation status of the color word. In that task, the ink was implicitly in conflict with the color meaning and the participants did not rely on the color or semantic clues to reach a decision. Therefore, significantly larger LPC amplitudes in the incongruent trials relative to the congruent trials for rotation judgment can only be explained by stimulus conflict. Our current results were also partially consistent with those of Chen et al. (2011), who found a relatively weak stimulus conflict effect in the 600–800 ms time window in the parietal region and found a strong response conflict in the 600–1200 ms time window in frontal regions. However, there are two key differences between the present experiment and that of Chen et al.

The first is that Chen et al. included a color-key mapping learning phase. It has been found that learning reduces the effects of semantic conflict (i.e., stimulus conflict) in the Stroop task (Chen, Jiang, Zhao, & Chen, 2010). Because the LPC may reflect the

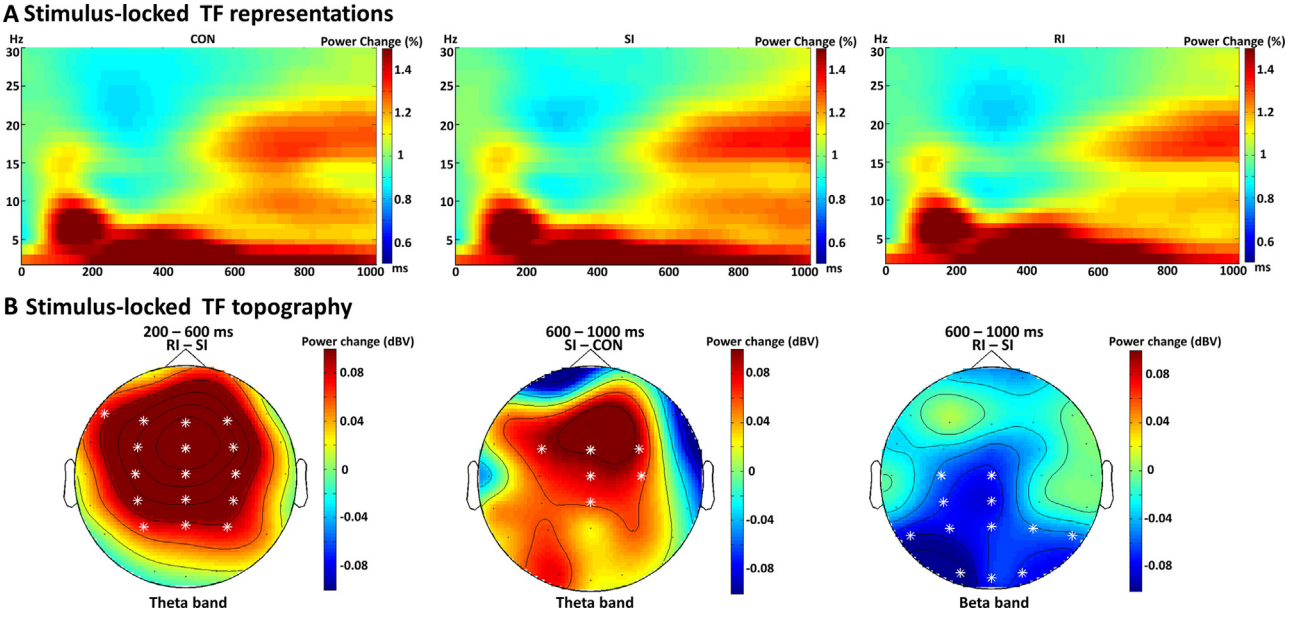


**Fig. 4.** Results of the stimulus-locked time-frequency (TF) analyses. (A) TF representations the average power of all electrodes of each condition in the stimulus-locked analyses. (B) Topography of significant TF clustering in the stimulus-locked analyses.
Note. * Indicates an electrode showing a significant condition effect. CON: congruent trial; SI: stimulus incongruent trial; RI: response incongruent trial.

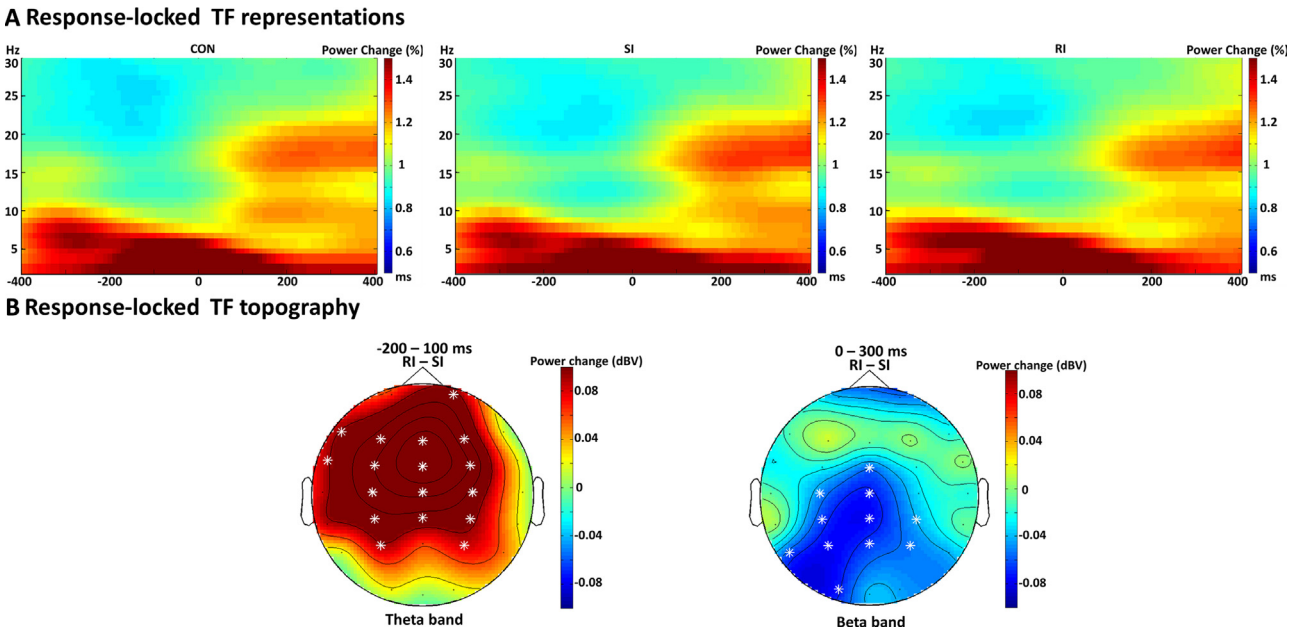


**Fig. 5.** Results of the response-locked time-frequency (TF) analyses. (A) TF representations the average power of all electrodes of each condition in the response-locked analyses. (B) Topography of significant TF clustering in the response-locked analyses.
Note. * Indicates an electrode showing a significant condition effect. CON: congruent trial; SI: stimulus incongruent trial; RI: response incongruent trial.

conflict between automatic semantic access and color ink (Liotti et al., 2000), it is likely that the weak stimulus effect in Chen et al. might be attributed to learning modulation. The practice effect may also affect our results. Indeed, we found an RT practice effect on stimulus interference (SI – CON) when we compared the first 60 correct trials with the last 60 correct trials. However, we did not observe such a learning effect on LPC. Our findings may differ from these earlier results due to explicit learning instructions used in Chen et al., which showed a deeper influence on the stimulus interference effect. Further studies should largely increase the number of trials to comprehensively test the practice effect on behavioral interference and ERP components. It should be noted that the practice effect could also contribute to the non-significant stimulus RT interference but affect the LPC effect less. This is consistent with a recent notion that final overt level RT may not be differentially sensitive to stimulus or response conflict (Killikelly & Szucs, 2013).

The second difference is the mean RT difference between the two studies. While the mean RT of the present study (CON, SI, RI = 470, 474, 502 ms) was consistent with previous reports [CON, SI, RI = 545, 561, 582 ms in De Houwer (2003), and CON, SI, RI = 599, 614, 634 ms for young adults in Killikelly and Szucs (2013)], Chen et al. (2011) observed longer mean RT (CON, SI, RI = 805, 843, 965 ms). The response conflict in the 800–1200 ms time window in Chen et al. may be due to the long RT.

The dissociable ERP effect can be further explained by a parallel distributed processing model (Zhang, Zhang, & Kornblum, 1999). According to this model, the Stroop stimuli have multiple dimensions. The stimulus and response conflict are caused by interference among overlapping dimensions. In the SI condition, this is a stimulus-stimulus overlap, i.e., a similarity between two stimulus dimensions, whereas in the RI condition, this is a stimulus-response overlap, i.e., a similarity between a stimulus dimension and a response dimension.

### 4.2. LRP results

Regarding LRP, inconsistent results were found in previous studies. For instance, some studies have reported a more negative mean amplitude in the incongruent condition than in the congruent condition in correct trials (Szucs & Soltesz, 2007; Szucs, Soltesz, Bryce, et al., 2009), while a reversed amplitude pattern has also been reported (Lansbergen & Kenemans, 2008). In the present study, by taking advantage of the 2-1 mapping paradigm, we found that larger LRP negativity was associated with response conflict in both stimulus- and response-locked analyses. Because response conflict was only involved in the RI condition in the 2-1 mapping paradigm, the larger LRP negativity in the RI compared with the other two conditions should be attributed to response conflict.

### 4.3. Theta effect

Based on our success in isolating the N450 and the LPC effect for stimulus and response conflict, we sought to reveal potential dissociations in TF representations for the two forms of conflict. The response-locked data only showed a response conflict effect immediately before and after the response in the theta band, in line with the hypothesis. However, the TF results in the stimulus-locked analyses revealed that the power change in the theta band was associated with both stimulus and response conflict. The association between theta band power changes and general conflict was consistent with previous studies (Brittain et al., 2012; Hanslmayr et al., 2008; Wen, Zhao, & Yao, 2006). For instance, in the Flanker 2-1 mapping task, the theta power change was associated with both response and stimulus conflict (Nigbur et al., 2012). The theta band power increase may have resulted from the fact that participants tried to enhance cognitive control when facing the conflict (Cavanagh et al., 2009, 2011; Nigbur et al., 2011). The novel finding in the present study was that there may be a temporal dissociation between stimulus and response conflict because the response conflict was dominant in earlier time windows and was followed by the stimulus conflict effect in later time windows in stimulus-locked analyses. Furthermore, the time windows of the earlier and later theta band effects in the stimulus-locked analyses were parallel with those of the N450 and LPC effects. This consistency could be further evidence that the stimulus conflict and response conflict in Stroop effects can be distinguished on electrophysiological indices.

The theta band effect was reported in ACC (Hanslmayr et al., 2008) and MFC (Cavanagh et al., 2009, 2011; Hanslmayr et al., 2008; Nigbur et al., 2011, 2012). Previous studies have also found N450 might be associated with activation in ACC (Botvinick et al., 2001; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003). In addition to the response effect in ACC found in fMRI studies (Kim et al., 2011; van Veen & Carter, 2005), it is reasonable to speculate that the ACC generated the N450 as well as the earlier response conflict-related theta band power change. This could be further investigated through a concurrent fMRI-EGG integration analysis.

### 4.4. Beta effect

We found that the beta band (13–20 Hz) power change was sensitive to response conflict in both stimulus- and response-locked results. This finding was in line with response conflict-related beta power changes in previous studies (Brittain et al., 2012; Grent-'t-Jong, Oostenveld, Jensen, Medendorp, & Praamstra, 2013; Wang et al., 2014). It should be noted that in the present study, the power change was significantly reduced in the RI relative to the SI. This pattern was consistent with the findings of Wang et al. and in contrast to those of Brittain et al. The difference might have occurred because like Wang et al., we employed scalp recording, while Brittain et al. employed intracranial recording in a specific region.

## 5. Conclusion

The aim of the present study was to isolate stimulus- and response-related ERP/EEG features. The 2-1 mapping paradigm revealed that the N450 and LPC were associated with response and stimulus conflict, respectively. Furthermore, different TF representations were experimentally isolated, such that stimulus and response conflict were associated with theta band power changes in different time windows and response conflict was additionally associated with beta band power changes. These results reveal that stimulus and response conflict in the Stroop task are associated with different ERP/EEG features.

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