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## Electrophysiological dynamics reveal distinct processing of stimulus-stimulus and stimulus-response conflicts

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### Abstract

The present study examined electroencephalogram profiles on a novel stimulus-response compatibility (SRC) task in order to elucidate the distinct brain mechanisms of stimulus-stimulus (S-S) and stimulus-response (S-R) conflict processing. The results showed that the SRC effects on reaction times (RTs) and N2 amplitudes were additive when both S-S and S-R conflicts existed. We also observed that, for both RTs and N2 amplitudes, the conflict adaptation effects—the reduced SRC effect following an incongruent trial versus a congruent trial—were present only when two consecutive trials involved the same type of conflict. Time-frequency analysis revealed that both S-S and S-R conflicts modulated power in the theta band, whereas S-S conflict additionally modulated power in the alpha and beta bands. In summary, our findings provide insight into the domain-specific conflict processing and the modular organization of cognitive control.

**Descriptors:** Stimulus-response compatibility, Conflict adaptation, N2, Theta band

Although cognitive control can flexibly adapt our behavior to our goals by organizing thoughts and actions (Botvinick, Braver, Barch, Carter, & Cohen, 2001), performing a cognitive task does not always proceed smoothly. A general finding is that performance is hampered (i.e., slower or less accurate) when mappings of stimuli to responses are incongruent than when they are congruent (Proctor & Vu, 2006), a phenomenon known as stimulus-response compatibility (SRC) effect (Yamaguchi & Proctor, 2012). For example, during a typical Stroop task, people perform more slowly and less accurately when identifying the print color of an incongruent color word (e.g., “red” in blue ink) compared with a congruent color word (e.g., “blue” in blue ink; Stroop, 1935). Similarly, during a typical Simon task, people make slower and less accurate responses when the stimulus location is opposite to the location of the assigned response than when it is the same (Simon, 1990). In addition, for the above SRC tasks, performance is also modulated by the congruency on the previous trial. People tend to speed up their responses to incongruent trials but slow down the responses to congruent trials following previous incongruent trials

(Egner, Delano, & Hirsch, 2007; Funes, Lupianez, & Humphreys, 2010; Larson, Kaufman, & Perlstein, 2009; Torres-Quesada, Funes, & Lupianez, 2013). For example, people tend to respond more quickly to incongruent trials following incongruent trials (iI) than incongruent trials following congruent trials (cI). And they tend to respond to congruent trials following incongruent trials more slowly (iC) than congruent trials following congruent trials (cC). This phenomenon is called the conflict adaptation (CA) effect (Gratton, Coles, & Donchin, 1992). In the manual Stroop task, both the SRC and CA effects are stimulus-based processing (S-S conflict), since the conflict stems from the incongruence between task-relevant (e.g., ink color) and task-irrelevant (e.g., word meaning) stimulus features (Egner et al., 2007; Liu, Park, Gu, & Fan, 2010). In the Simon task, however, both the SRC and CA effects are response-based processing (S-R conflict), since the conflict results from the incongruence between a task-irrelevant stimulus feature (e.g., the location of the stimuli) and a response feature (Egner et al., 2007). However, whether resolving S-S and S-R conflicts recruits distinct control mechanisms or relies on shared central resources is still in dispute.

The conflict-monitoring (CM) model, an influential account of cognitive control, is usually considered to be domain general. It proposes that a single “all-purpose” conflict-control loop consisting of a conflict monitor module and an executive control module could generally resolve conflict information by reinforcing the top-down biasing processes associated with the current task set (Botvinick et al., 2001). The CM model predicts that nonadditive SRC effects and cross-conflict-type CA effects will occur, as both S-S and S-R conflicts share a centralized modular architecture of cognitive control. However, the dimensional overlap (DO)

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framework (Kornblum, Hasbroucq, & Osman, 1990) has been contrasted with the CM model (Egner, 2008). According to the DO taxonomy, for any S-R ensembles that consist of all three attributes (task-relevant stimulus dimension, task-irrelevant stimulus dimension, and response dimension), the SRC effects can occur independently when at least two dimensions overlap with each other. Therefore, the DO model predicts that SRC effects stemming from S-S (task-relevant stimulus dimension, task-irrelevant stimulus dimension) and S-R (task-irrelevant stimulus dimension, response dimension) conflicts simultaneously can additively affect performance (Kornblum, 1994). Based on the DO theory, the domain-specific model holds that distinct or parallel conflict-control loops are involved in processing S-S and S-R conflicts at both the conflict-monitoring and executive control stages (Egner, 2008). In this way, the domain-specific model predicts that only the within-conflict-type CA effects would be observed while cross-conflict-type CA effects will not occur, because distinct cognitive control mechanisms are engaged by S-S and S-R conflicts in parallel.

Several behavioral and neuroimaging studies support the distinct processing of S-S and S-R conflicts. For example, studies that combined the manual Stroop and Simon tasks have shown that the S-S and S-R conflict effects are additive (Liu et al., 2010; Simon, 1990). By combining the Stroop/flanker conflict with the Simon conflict within a single task, some studies observed that the CA effect was specific to the same type of conflict (S-S or S-R conflicts; Akcay & Hazeltine, 2011; Egner et al., 2007; Funes et al., 2010). Functional magnetic resonance imaging (fMRI) studies have also proposed different “brain conflict detectors” for S-S and S-R conflicts, in which the resolution of the S-R conflict was distinguished by the modulation of activity in the premotor cortex, the rostral portion of the dorsal cingulate cortex, and the posterior cingulate cortex, whereas the resolution of the S-S conflict was distinguished by the modulation of activity in the parietal cortex and the caudal portion of the dorsal cingulate cortex (Egner et al., 2007; Frühholz, Godde, Finke, & Herrmann, 2011).

Although increasing electroencephalogram (EEG) evidence has demonstrated that the conflict-related N2 component is an effective indicator of conflict processing in SRC tasks, few studies have directly compared EEG signals during the combined processing of S-S and S-R conflicts. The conflict-related N2 occurs approximately 250–350 ms after stimulus presentation (Folstein & Van Petten, 2008), and this component has consistently been observed in the Stroop task (West & Alain, 1999) as well as in the Simon task (Böckler, Alpay, & Stürmer, 2011). The N2 amplitude is thought to index the degree of conflict, with its amplitude increasing as a function of conflict levels presented (Forster, Carter, Cohen, & Cho, 2011). Additionally, recent event-related potential (ERP) studies have shown that the N2 amplitude is sensitive to CA effects; that is, the difference in the N2 amplitudes decreases, along with the reduced conflict effect, following an incongruent trial compared with when following a congruent trial (Clayson & Larson, 2011a, 2011b, 2012). To our knowledge, only one previous ERP study combined the color-dot flanker and the Simon task and found that S-S and S-R conflicts relied on distinct brain mechanisms of conflict processing (Frühholz et al., 2011). However, in that experiment, the Simon task was not “pure,” because the S-R conflict actually came from the overlap of the locations of the target and the response, as well as from the overlap of the locations of the flankers and the response.

In addition to ERP analysis, EEG oscillations within special frequency bands can indicate particular patterns of neural activity

and cognitive functions (Roach & Mathalon, 2008). Previous studies showed that cognitive control demands in S-S and S-R conflict situations led to an increase in frontal midline theta rhythm (Cohen & Cavanagh, 2011; Hanslmayr et al., 2008; Nigbur, Cohen, Ridderinkhof, & Stürmer, 2012), which might play a pivotal role in performance monitoring and conflict resolution processes. However, because few studies have examined the combined processing of S-S and S-R conflicts within a single task, it is still unclear whether particular frequency bands relate to S-S or S-R conflict situations.

To better investigate whether distinct networks that operate on S-S and S-R conflicts exist, we combined the manual spatial Stroop task (S-S conflict) and the Simon task (S-R conflict) in a single EEG experiment. We hypothesized that if specialized conflict-control loops could operate on S-S and S-R conflicts in parallel, then behavioral performance, N2 amplitude, and particular frequency bands would be independently modulated by S-S and S-R conflict processing. Specifically, both types of conflicts would additively modulate behavioral performance and only affect the resolution of the same type but would not affect the other type of consecutive trial. Furthermore, the N2 amplitudes would exhibit an additive effect of S-S and S-R conflicts and show the specificity of the CA effect. Finally, S-S and S-R conflicts would differentially modulate frequency bands, reflecting the recruitment of separate neural mechanisms.

## Method

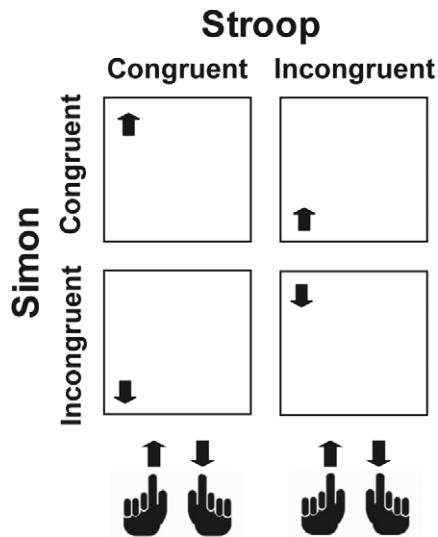
### Participants

Thirty-four university students ( $22.85 \pm 0.45$  years old, 18 men) participated in the present EEG experiment. All participants were right-handed and had normal or corrected-to-normal vision. These participants reported no history of neurological or psychiatric disorders. Each participant voluntarily enrolled and signed an informed consent statement prior to the study. This study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

### Stimuli and Procedures

Participants completed a Simon-spatial-Stroop task that was modified from our previous study (Li, Nan, Wang, & Liu, 2014). This task consisted of one training block of 20 trials and six testing blocks. During the training block, one half of the participants were asked to press the F key with their left index finger in response to an upward arrow and to press the J key with their right index finger in response to a downward arrow. The other half of the participants were trained with the opposite mapping (i.e., press the F key to a downward arrow and press the J key to an upward arrow). On each trial, an arrow was presented for 600 ms at the center of the screen, followed by a fixation of 1,900 ms.

During the testing block, the participants were asked to respond to the direction of the arrow as quickly and accurately as possible according to the rules on which they were trained. Each trial started with a fixation of  $200 \pm 100$  ms. Then, an arrow was presented for 600 ms, followed by another fixation of  $1,700 \pm 100$  ms. The arrow was presented at one of four possible locations (top left, top right, bottom left, and bottom right) within a visual angle of  $5^\circ \times 5^\circ$  (see Figure 1). Based on the relationship between the location and the direction of the arrow (stimulus-stimulus, S-S) and between the location of the arrow and the side of the response



**Figure 1.** Experimental design for the Simon-spatial Stroop task. The stimuli consisted of an upward or downward arrow that was presented at one of four possible locations: top left, top right, bottom left, and bottom right. The location of the arrow could be either the same or the opposite direction as the arrow was pointing (i.e., up or down; S-S conflict) as well as either the same or the opposite side as the required response (i.e., left or right; S-R conflict).

(stimulus-response, S-R), each trial could be classified into one of four conditions in a 2 (Conflict Type: S-S vs. S-R)  $\times$  2 (Congruence: congruent vs. incongruent) factorial design. The task was comprised of 480 trials, which were equally divided into six blocks. Each block consisted of an equal number of different trial types that were randomly mixed, with the restriction that the same stimulus or the same response did not repeat more than three times in succession.

In addition to the above two factors, we recoded the offline sequential effects by creating two additional factors. One factor was to code the level of congruence on the previous trial. The fourth factor was to code whether the types of conflicts on two consecutive trials were repeated or alternated. Specifically, conflict repetition referred to both trials consisting of S-S or S-R conflicts, and conflict alternation referred to two trials consisting of different conflicts (either S-S/S-R or S-R/S-S).

### EEG Recordings and Offline Processing

The EEG was recorded from 64 scalp sites using Ag/AgCl electrodes arranged in an elastic cap according to an extension of the International 10–20 system (NeuroScan Inc., Herndon, VA). Vertical eye movements were recorded by two electrodes positioned above and below the left eye. The horizontal electrooculogram was recorded using lateral electrodes from both eyes. Impedances were below 5 k $\Omega$  for all recording sites. EEG signals were amplified using a NeuroScan SymAmps2 amplifier with a band-pass of 0.05–100 Hz and sampled with 500 Hz.

All scalp electrodes were referenced to the left mastoid online and were referenced to the average of the left and right mastoids offline. Each epoch started from 100 ms before the onset of the stimulus and lasted for 800 ms, with the first 100 ms as the baseline. Trials with errors or trials that were contaminated with artifacts exceeding  $\pm 100 \mu\text{V}$  were excluded from the analysis. The

data were averaged for each condition and then digitally low-pass filtered at 30 Hz (24 dB/octave) with zero phase shift.

### Statistical Analyses

**Behavioral and ERP data analysis.** Behavioral effects were indexed using mean response times (RT) of correct responses and error rates (ER) for each condition. The ERPs of correct responses were averaged for each condition. The time window for N2 was identified using the following protocol. First, we detected the peak latencies of all conditions at the midline electrodes (Fz, FCz, Cz, CPz, and Pz) and calculated the mean of these latencies (290 ms). For the N2 component, a 100-ms time window was centered on the mean peak latency. Therefore, the SRC effects on the N2 mean amplitude were analyzed within 240–340 ms after stimulus onset. Furthermore, to control feature integration (Hommel, Proctor, & Vu, 2004) and the repetition priming effects (Mayr, Awh, & Laury, 2003), we excluded trials with exact S-R repetitions from the analysis of the CA effects. The mean number of trials retained for each condition are listed in Table 1. A one-way analysis of variance (ANOVA) revealed that the numbers of trials for different conditions were not significantly different from each other,  $F(15,495) = 1.73, p > .05$ , which eliminated the potential influence of different signal-noise ratios to statistical comparison.

For each dependent variable, a repeated measures ANOVA was performed and evaluated at  $p < .05$ . Greenhouse-Geisser corrections were conducted when necessary. Additive SRC effects were calculated for RT and ER, in which the 2  $\times$  2 factors tested were conflict type (S-S vs. S-R) and current trial congruence (congruent vs. incongruent). Four potential CA effects were analyzed for RT and ER within and across S-S and S-R conflicts, respectively, in which the 2  $\times$  2 factors tested were previous trial congruence (congruent vs. incongruent) and current trial congruence (congruent vs.

**Table 1.** Means (SE) of the Reaction Times (ms), Error Rates (%), N2 Amplitudes ( $\mu\text{V}$ ), and Number of Trials Retained per Experimental Conditions for the Simon-Spatial Stroop Task

Trial N-1/Trial N		cC	cI	iC	iI
Stroop/Stroop	RT	451 (7)	487 (6)	473 (6)	481 (6)
	ER	2 (.5)	6 (.7)	5 (.6)	5 (.7)
	N2	4.2 (.7)	3.0 (.6)	3.6 (.6)	3.1 (.6)
	<i>n</i>	68 (1)	64 (2)	67 (2)	68 (1)
Simon/Simon	RT	453 (7)	489 (7)	468 (6)	482 (6)
	ER	2 (.4)	7 (.9)	5 (.7)	5 (.7)
	N2	4.1 (.6)	3.0 (.6)	3.5 (.6)	3.2 (.6)
	<i>n</i>	69 (2)	65 (2)	67 (2)	66 (2)
Stroop/Simon	RT	456 (6)	482 (7)	466 (6)	489 (6)
	ER	3 (.5)	5 (.7)	4 (.5)	6 (.9)
	N2	4.2 (.6)	3.1 (.7)	3.5 (.6)	3.2 (.5)
	<i>n</i>	68 (2)	64 (2)	68 (2)	66 (2)
Simon/Stroop	RT	460 (7)	482 (6)	464 (7)	486 (5)
	ER	4 (.5)	5 (.7)	3 (.5)	6 (.7)
	N2	3.9 (.6)	3.3 (.6)	3.9 (.7)	2.8 (.6)
	<i>n</i>	67 (1)	66 (2)	68 (2)	65 (2)

*Note.* Stroop/Stroop = Stroop congruency (S-S conflict) trial preceded by a Stroop congruency (S-S conflict) trial; Simon/Simon = Simon congruency (S-R conflict) trial preceded by a Simon congruency (S-R conflict) trial; Stroop/Simon = Stroop congruency (S-S conflict) trial preceded by a Simon congruency (S-R conflict) trial; Simon/Stroop = Simon congruency (S-R conflict) trial preceded by a Simon congruency (S-R conflict) trial; RT = reaction times; ER = error rates; N2 = N2 amplitudes; *n* = number of trials.

incongruent). The electrode site (Fz, FCz, Cz, CPz, and Pz), as an additional factor, was applied to the calculation of mean N2 amplitudes for additive SRC effects and CA effects.

**Time-frequency analysis.** The same preprocessing steps were performed with the NeuroScan software, except that stimulus-locked epochs extended from  $-800$  ms to  $1,498$  ms relative to the onset of stimulus presentation. These segmented EEG data were rereferenced to the average reference without averaging and filtering. The evoked event-related spectral perturbation (ERSP)—mean change in spectral power (in dB) from baseline, and intertrial coherence (ITC)—strength (0 to 1) of phase locking of EEG signals to the events, were calculated using the open source toolbox EEGLAB (Delorme & Makeig, 2004) in MATLAB (The Mathworks, Inc.). Using the *newtimef* function, spectral analyses were computed on the entire epochs, and the baseline was corrected to a 100-ms prestimulus interval. Hanning-tapered sinusoidal wavelets were used to do the time-frequency transformation, with three cycles at the lowest frequency (4 Hz), and the number of cycles in the wavelets used for higher frequencies was expanded, reaching half the number of cycles in the equivalent fast Fourier transform (FFT) window at the highest frequency. Forty frequency points were calculated, ranging from 4 to 30 Hz. Significant event-related SRC effects were assessed using parametric statistical methods. Given that difference maps showed the frequencies of interest (4–30 Hz) between the incongruent and congruent conditions peaked at FCz, the ERSP and ITC effects of S-S and S-R conflicts at the FCz site were further quantified using paired *t* tests for each frequency. The frequencies of interest were theta1 (4–5 Hz), theta2 (6–8 Hz), alpha1 (9–10 Hz), alpha2 (11–12 Hz), beta1 (13–19 Hz), and beta2 (20–30 Hz; Babiloni et al., 2013). Conflict type and congruence factors were the same as in the behavioral and ERP analyses. Because ERSP and ITC have lower temporal resolution than ERP, their analysis focused on the respective frequency modulation of S-S and S-R conflict effects with wider time windows (200–400 ms), starting from 200 ms after stimulus onset.

## Results

### Behavioral Results

**Additive SRC effects.** RT results showed that the main effects of S-S current trial congruence,  $F(1,33) = 104.28$ ,  $p < .001$ ,  $\eta_p^2 = .76$ , and S-R current trial congruence,  $F(1,33) = 74.92$ ,  $p < .001$ ,  $\eta_p^2 = .69$ , were significant, with slower RTs for incongruent trials ( $M_{S-S} = 488$  ms,  $M_{S-R} = 490$  ms) than for congruent trials ( $M_{S-S} = 467$  ms,  $M_{S-R} = 466$  ms). Conflict type and current trial congruence did not interact,  $F(1,33) = 2.67$ ,  $p > .05$ ,  $\eta_p^2 = .08$ , which was consistent with previous research (Akçay & Hazeltine, 2011; Funes et al., 2010). Furthermore, the SRC effects caused by S-S and S-R conflicts were not significantly correlated with each other,  $r(32) = .15$ ,  $p > .05$ , which implied relative independence of S-S and S-R conflict processing.

The results for the ER were similar to those obtained for the RTs. The main effects of S-S current trial congruence,  $F(1,33) = 22.92$ ,  $p < .001$ ,  $\eta_p^2 = .41$ , and S-R current trial congruence,  $F(1,33) = 31.16$ ,  $p < .001$ ,  $\eta_p^2 = .49$ , were significant, with participants making more errors on the incongruent trials ( $M_{S-S} = 6\%$ ,  $M_{S-R} = 7\%$ ) than on the congruent trials ( $M_{S-S} = 4\%$ ,  $M_{S-R} = 3\%$ ). The Conflict Type  $\times$  Current Trial Congruence interaction was not significant,  $F(1,33) = 3.21$ ,  $p > .05$ .

**Conflict adaptation effects.** The CA results of the mean RT and ER are listed in Table 1. For the RTs, within the S-S conflict, the main effects of previous trial congruence,  $F(1,33) = 22.54$ ,  $p < .001$ ,  $\eta_p^2 = .41$ , and current trial congruence,  $F(1,33) = 75.36$ ,  $p < .001$ ,  $\eta_p^2 = .70$ , were significant. Furthermore, the interaction effect of Previous  $\times$  Current Trials was significant,  $F(1,33) = 51.90$ ,  $p < .001$ ,  $\eta_p^2 = .61$ , which reflected a reduction in the SRC effect following incongruent trials (7 ms) compared with that following congruent trials (36 ms), which was typically observed in the CA effect (see Figure 2). This interaction resulted from a combination of faster responses to iI trials than for cI trials (iI – cI =  $-6$  ms,  $p < .05$ ), and slower responses to iC than for cC trials (iC – cC = 22 ms,  $p < .001$ ). Similarly, within the S-R conflict, the main effects of previous trial congruence,  $F(1,33) = 5.51$ ,  $p < .05$ ,  $\eta_p^2 = .14$ , and current trial congruence,  $F(1,33) = 72.08$ ,  $p < .001$ ,  $\eta_p^2 = .69$ , were significant. Furthermore, the interaction effect of Previous  $\times$  Current Trials was significant,  $F(1,33) = 38.57$ ,  $p < .001$ ,  $\eta_p^2 = .54$ , reflecting a reduction in the SRC effect following incongruent trials (14 ms) compared with that following congruent trials (36 ms). Again, this interaction was mediated by a combination of faster responses to incongruent trials (iI – cI =  $-8$  ms,  $p < .01$ ), and slower responses to congruent trials (iC – cC = 15 ms,  $p < .001$ ). However, when analyzing current trial S-S congruence as a function of previous trial S-R congruence, we found the main effects of previous trial congruence,  $F(1,33) = 25.78$ ,  $p < .001$ ,  $\eta_p^2 = .44$ , and current trial congruence,  $F(1,33) = 70.47$ ,  $p < .001$ ,  $\eta_p^2 = .68$ , but no Previous  $\times$  Current Trial interaction effect,  $F(1,33) = .75$ ,  $p > .05$ , indicating the absence of the typical CA effect. Similarly, when assessing current trial S-R congruence as a function of previous trial S-S congruence, we found the main effects of previous trial congruence,  $F(1,33) = 8.77$ ,  $p < .01$ ,  $\eta_p^2 = .21$ , and current trial congruence,  $F(1,33) = 73.40$ ,  $p < .001$ ,  $\eta_p^2 = .69$ , but no Previous  $\times$  Current Trial interaction effect,  $F(1,33) = 0.00$ ,  $p > .05$ .

The results for the ER were similar to those obtained for the RTs. For the S-S conflict, a main effect of current trial congruence,  $F(1,33) = 16.69$ ,  $p < .001$ ,  $\eta_p^2 = .34$ , was significant. Furthermore, the interaction effect of Previous  $\times$  Current Trials was significant,  $F(1,33) = 30.58$ ,  $p < .001$ ,  $\eta_p^2 = .48$ , with the SRC effect being reduced when following an incongruent trial (0%) compared with following a congruent trial (4%). This interaction was mediated by a combination of smaller ER for the iI trials than for the cI trials (iI – cI =  $-1\%$ ,  $p = .065$ ) and larger ER for the iC trials than for the cC trials (iC – cC = 3%,  $p < .001$ ). Similarly, for the S-R conflict, a main effect of current trial congruence,  $F(1,33) = 11.71$ ,  $p < .01$ ,  $\eta_p^2 = .26$ , was significant. Furthermore, the interaction effect of Previous  $\times$  Current Trials was significant,  $F(1,33) = 46.66$ ,  $p < .001$ ,  $\eta_p^2 = .59$ , reflecting a reduction in the SRC effect following incongruent trials (0%) compared with that following congruent trials (5%). This interaction was mediated by a combination of smaller ER for the iI trials than for the cI trials (iI – cI =  $-2\%$ ,  $p < .001$ ) and larger ER for the iC trials than for the cC trials (iC – cC = 3%,  $p < .001$ ). However, when analyzing current trial S-S congruence as a function of previous trial S-R congruence, we found a main effect of current trial congruence,  $F(1,33) = 12.31$ ,  $p < .001$ ,  $\eta_p^2 = .27$ , but no Previous  $\times$  Current Trial interaction effect,  $F(1,33) = .12$ ,  $p > .05$ , indicating the absence of the typical CA effect. Similarly, when assessing current trial S-R congruence as a function of previous trial S-S congruence, we found a main effect of current trial congruence,  $F(1,33) = 16.61$ ,  $p < .001$ ,  $\eta_p^2 = .34$ , but no Previous  $\times$  Current Trial interaction effect,  $F(1,33) = 1.99$ ,  $p > .05$ . The ERs were positively associated with

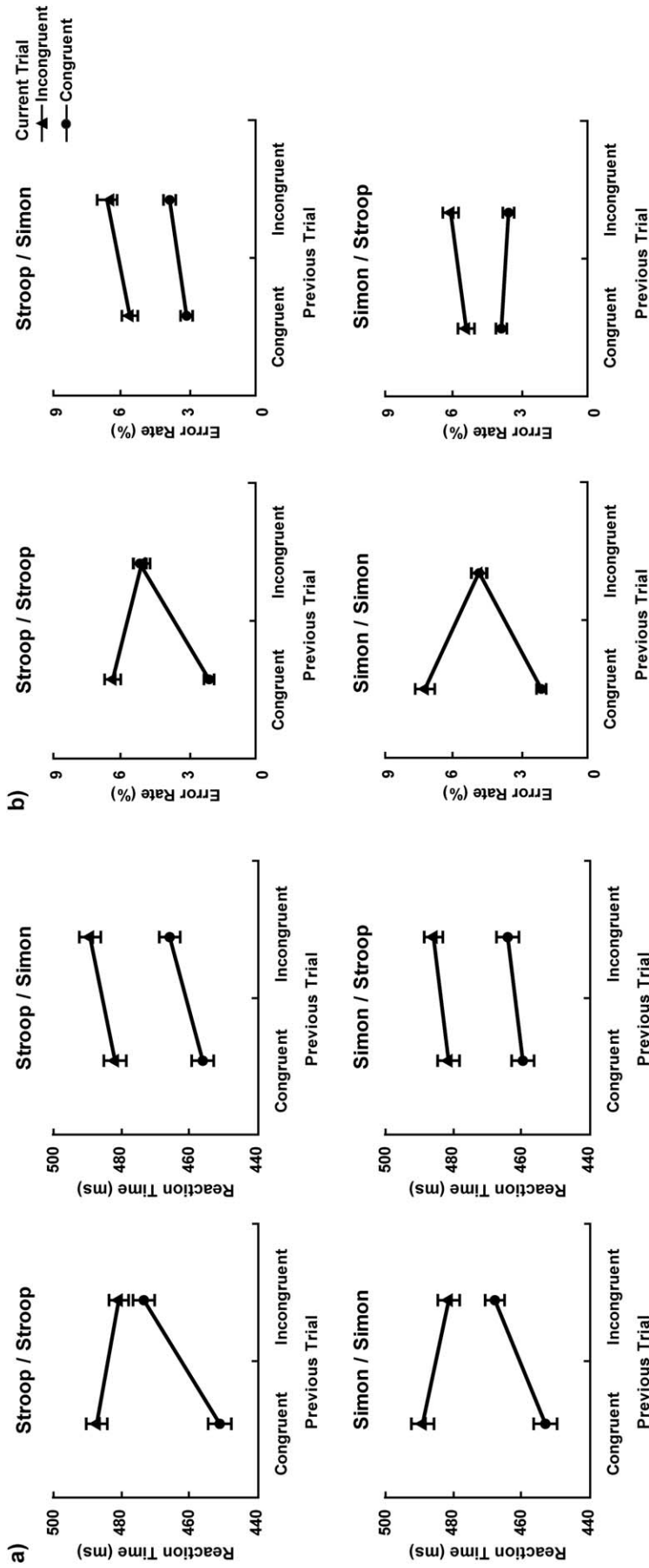


Figure 2. Behavioral results: (a) reaction times and (b) error rates for the Simon-spatial-Stroop task. The labels and legends are the same as in Table 1.

the RTs across the conditions, ruling out a speed–accuracy trade-off effect.

### ERP Results

**Additive SRC effects.** The main effects of S-S current trial congruence,  $F(1,33) = 41.08$ ,  $p < .001$ ,  $\eta_p^2 = .56$ , and S-R current trial congruence,  $F(1,33) = 28.00$ ,  $p < .001$ ,  $\eta_p^2 = .46$ , were significant, with more negative N2 amplitudes to incongruent trials than to congruent trials. The main effect of electrode site was significant,  $F(4,132) = 66.69$ ,  $p < .001$ ,  $\eta_p^2 = .67$ , with more negative N2 amplitudes at Fz and FCz compared with Cz, CPz, and Pz ( $ps < .05$ ). Furthermore, the S-S Congruence  $\times$  Electrode Site interaction was significant,  $F(4,132) = 12.03$ ,  $p < .001$ ,  $\eta_p^2 = .27$ , because the N2 amplitude difference between incongruent and congruent S-S trials varied significantly across electrode sites ( $ps < .01$ ) with a significantly larger difference at FCz, Cz, CPz, and Pz compared with Fz ( $ps < .01$ ). The conflict type and current trial congruence did not interact,  $F(1,33) = 0.32$ ,  $p > .05$ , indicating that the N2 amplitude showed an additive effect when both S-S and S-R conflicts were present. Furthermore, no other interaction reached significance.

**Conflict adaptation effect.** The mean N2 amplitudes for five electrode sites are listed in Table 1. The results showed that, for the S-S conflicts, the main effect of current trial congruence was significant with more negative N2 amplitudes to incongruent trials than to congruent trials,  $F(1,33) = 24.45$ ,  $p < .001$ ,  $\eta_p^2 = .43$ . The three-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence  $\times$  Electrode Site,  $F(4,132) = 0.14$ ,  $p > .05$ , was not significant. Reliable CA effect on N2 amplitude was shown as indicated by a significant Previous Trial Congruence  $\times$  Current Trial Congruence interaction,  $F(1,33) = 5.36$ ,  $p < .05$ ,  $\eta_p^2 = .14$ , with the SRC effect being reduced when following an incongruent trial (SRC effect:  $-0.48 \mu\text{V}$ ) compared with following a congruent trial (SRC effect:  $-1.20 \mu\text{V}$ ; see Figure 3). The N2 amplitudes were less negative for the cC than for the iC trials,  $p < .05$ ; no differences were observed for the cI and iI trials,  $p > .05$ . Similarly, for the S-R conflicts, the main effect of current trial congruence was significant with more negative N2 amplitudes to incongruent trials than to congruent trials,  $F(1,33) = 10.13$ ,  $p < .01$ ,  $\eta_p^2 = .24$ . The three-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence  $\times$  Electrode Site was significant,  $F(4,132) = 3.34$ ,  $p < .05$ ,  $\eta_p^2 = .09$ . Follow-up analyses indicated significant CA effects over frontocentral electrode sites (Fz, FCz, Cz, and CPz) ( $ps < .01$ ). The N2 amplitudes across frontocentral electrode sites were less negative for the cC than for the iC trials,  $p < .05$ ; no differences were observed for the cI and iI trials,  $p > .05$ . However, when analyzing current trial S-S congruence as a function of previous trial S-R congruence, we found a main effect of current trial congruence,  $F(1,33) = 10.55$ ,  $p < .01$ ,  $\eta_p^2 = .24$ , but no three-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence  $\times$  Electrode Site,  $F(4,132) = .37$ ,  $p > .05$ , or two-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence,  $F(1,33) = 2.87$ ,  $p > .05$ , indicating the absence of the typical CA effect. Similarly, when assessing current trial S-R congruence as a function of previous trial S-S congruence, we found a main effect of current trial congruence,  $F(1,33) = 22.93$ ,  $p < .001$ ,  $\eta_p^2 = .41$ , but no three-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence  $\times$  Electrode Site,  $F(4,132) = 1.96$ ,  $p > .05$ , or two-way interaction of Previous Trial Congruence  $\times$  Current Trial Congruence,  $F(1,33) = 1.33$ ,  $p > .05$ , indicating the absence of the typical CA effect.

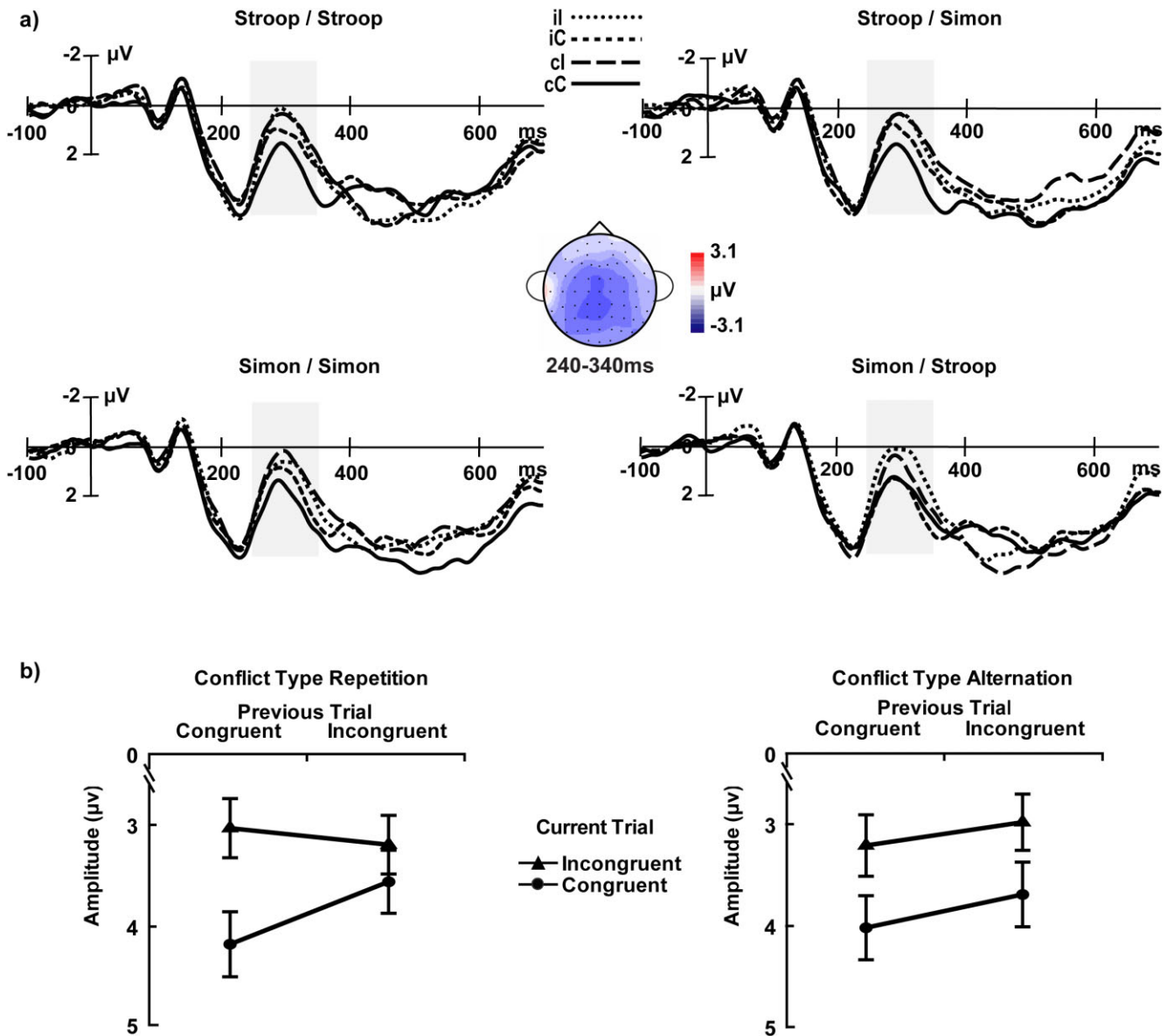
### Time-Frequency Analyses

The results of the SRC effects on ERSP for S-S and S-R conflicts are displayed in Figure 4. The ITC results did not reach the significance level and are not shown. The results of spectral power at the FCz site revealed significant S-S SRC effects in theta1,  $t(1,33) = 4.60$ ,  $p < .001$ ; theta2,  $t(1,33) = 5.99$ ,  $p < .001$ ; alpha1,  $t(1,33) = 2.15$ ,  $p < .05$ ; and beta2 power,  $t(1,33) = 2.49$ ,  $p < .05$ , which was due to stronger phasic enhancement for incongruent trials compared with the congruent trials. As well, significant S-R SRC effects were found in theta1,  $t(1,33) = 6.80$ ,  $p < .001$ ; theta2,  $t(1,33) = 4.64$ ,  $p < .001$ , which were due to stronger phasic enhancements for incongruent trials compared with the congruent trials.

### Discussion

Overall, the findings of the Simon-spatial-Stroop task suggest that S-S and S-R conflicts have different neural correlates. First, behavioral data showed that conflict resolution was additive when both S-S and S-R conflicts existed and that each conflict only enhanced the resolution of its own type. Second, the ERP results showed that, from 240 to 340 ms, the N2 amplitudes indicated an additive effect and a domain-specific CA effect for S-S and S-R conflicts. Third, time-frequency analysis showed that, in addition to the common ERSP effects of both conflicts at the theta band (4–8 Hz), the S-S conflict additionally modulated the oscillation power in the alpha1 (9–10 Hz) and beta band (20–30 Hz).

Before assessing potential cross-conflict-type CA effects, the additive-factors method is critical to empirically establish the distinction of the conflicts involved (Egner, 2008). According to the logic of the additive-factors method, additive effects of two experimental variables or factors (such as main effects for both variables and no interaction) mean that the variables rely on separate processing streams. In contrast, interactive effects imply that the variables share at least one module with limited capacity in common (Sternberg, 1967). Our behavioral results showed that processing of S-S and S-R conflicts was additive, which accorded with previous findings in the factorially combined Stroop and Simon tasks (Li et al., 2014; Simon, 1990), and these data indicated that S-S and S-R conflicts were processed on independent levels. Additionally, N2 amplitude was sensitive to the degree of conflict (Forster et al., 2011). When N2 amplitude was used as an indicator for the degree of conflict, we found that the conflict type (S-S conflict vs. S-R conflict) and congruence (congruent vs. incongruent) had no interaction, which demonstrated that both S-S and S-R conflicts additively modulated the N2 amplitude. Similar findings were obtained in an ERP study in which the S-S conflict modulated the N2 and early P3 component (labeled “N2-eP3” complex) and the S-R conflict modulated the late P3b component. Accordingly, the simultaneous occurrence of S-S and S-R conflicts during double conflict trials resulted in a modulation of both early N2-eP3 and late P3b components, which resembled an additive effect of those modulations for single conflict trials (Frühholz et al., 2011). The authors noted that S-S and S-R conflicts modulated different ERP components and resulted in noninteractive effects; thus, they suggested that S-S and S-R conflict processing involved distinct neural loops. It is unclear why S-S and S-R conflicts modulated N2 amplitudes independently in our study, while they modulated different ERP components in the previous study (Frühholz et al., 2011). However, we noticed our study differed from the previous study in a number of ways, which might cause these differences.

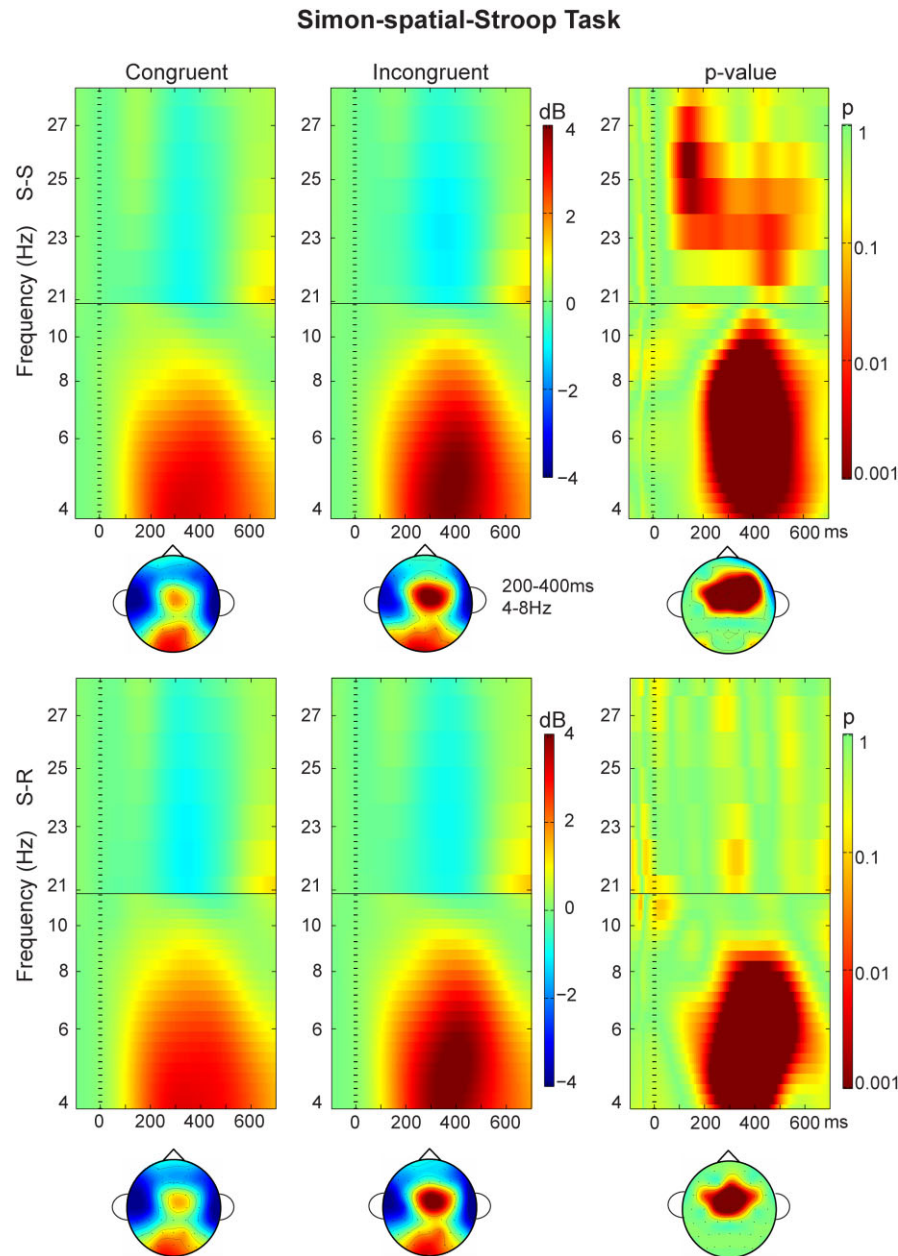


**Figure 3.** Grand-average ERP results. a: N2 activity at FCz for each previous-trial and current-trial pair and the topographic maps of the difference waveforms obtained by subtracting the ERPs on all S-S and S-R congruent trials from those on all S-S and S-R incongruent trials. The gray bars indicate the time intervals that were used for statistical analysis of the mean amplitude. The labels and legends are the same as in Table 1. b: N2 amplitude averaged across the midline electrode locations representing the CA effects, in which the Stroop/Stroop and the Simon/Simon trials, as well as the Stroop/Simon and the Simon/Stroop trials were combined together, respectively.

First, in our study, we used a combined spatial-Stroop and Simon conflict task, whereas they adopted a combined flanker and Simon conflict task. Second, in our experiment, the S-R conflict only came from the overlap between the response and the location of the target, whereas in their experiment the S-R conflict simultaneously came from the overlap across the response, the location of the target, and the location of the flankers. Our current findings were consistent with those in a previous study, in which we found that both S-S and S-R conflicts modulated N2 and P3 amplitudes, although the onset of S-S conflict on N2 component was slightly earlier than that of S-R conflict (Wang, Li, Zheng, Wang, & Liu, 2014).

Furthermore, many studies combining a Stroop task and a Simon task (Li et al., 2014; Simon, 1990) or a flanker task and an

auditory Simon task (Verguts, Notebaert, Kunde, & Wuhr, 2011) have reported additive effects for S-S and S-R conflict processing. However, other studies have reported nonadditive effects. For example, De Jong and colleagues examined a combination of the spatial-Stroop and Simon tasks and found interactions between the two tasks (De Jong, Liang, & Lauber, 1994). In their experiment, participants in the congruent/incongruent trials were asked to ignore the word meaning, but on the control trials, they were asked to attend to and respond to the word meaning. This procedure introduced task switching in different conditions, which may contribute to the interaction. Treccani and colleagues observed subadditive interactions when using a combination of flanker and Simon tasks, in which the stimuli consisted of a central presented target and a lateral presented flanker (Treccani, Cubelli, Sala, &



**Figure 4.** Time-frequency results. Time-frequency representations (ERSP) at FCz and topographic distribution of the theta band (4–8 Hz; 200–400 ms) for congruent and incongruent conditions of the different conflicts (S-S/S-R). Both the S-S and S-R conflicts enhanced the EEG power in the theta (4–8 Hz) band, whereas power in the alpha (9–10 Hz) and beta (20–30 Hz) bands was only modulated by S-S conflict.

Umiltà, 2009). Because both the spatial locations of the whole stimulus and the distracter were associated to responses, respectively, this setup could artificially introduce the interaction of S-S and S-R effects. Although we controlled for these potential confounding factors, it should also be noted that the additive RT and N2 effects in our results might not be sufficient to draw the conclusion of separate modules of S-S and S-R conflict processing. Because distinct modules can lead to these additive effects, additivity alone may not necessarily imply distinct processing of these conflicts. Therefore, converging measures, such as within- and cross-conflict CA effects, are necessary to examine the relative independence of S-S and S-R conflict effects.

Some researchers have found that the CA effect was domain specific, but with some confounding factors, such as the influence

of repetition (Egner et al., 2007; Funes et al., 2010; Wendt, Kluwe, & Peters, 2006). After controlling/removing the repetition effects, other studies also demonstrated that the CA effect was domain specific (Akçay & Hazeltine, 2011; Funes et al., 2010). However, the above-mentioned confound for those additive-factors studies also existed in these studies, due to the conflicts stemming from the overlapping of the task-relevant stimulus, the task-irrelevant stimulus, and the response, thus limiting the conclusion. After eliminating the above confounding factors, we still found a clear pattern that the CA effect was domain specific and was absent for cross-conflict-type condition. These results generally supported the domain specificity view of cognitive control, which argued that cognitive control operated in a specific way and was not generic to different types of conflicts (Egner, 2008).



Similarly, our ERP results revealed that the N2 amplitudes only showed reliable conflict adaptation when the same type of conflict was repeated. These results coincided with findings from recent ERP studies, in which N2, an electrophysiological index of cognitive control, was sensitive to the CA effects within the same type of conflict (Clayson & Larson, 2011a, 2011b, 2012). Critically, our study further revealed that the conflict adaptation of the N2 amplitudes disappeared completely when the type of conflict alternated across the trials. These data suggest that, when consecutive trials come from the same type of conflict, the significant interaction between the previous and current trial congruence arises because high conflict on an incongruent trial induces an up-regulation in cognitive control; this increased cognitive control results in the improved selection of target information in the following trial, which is reflected by faster responses to incongruent trials (reduced interference) and slower responses to congruent ones (reduced facilitation). However, when consecutive trials are from distinct types of conflict that involve independent processing mechanisms, the top-down cognitive control influences would be independent across the consecutive trials, and the CA effect would not be observed (Egner, 2008). These findings broadly support the domain-specific model. However, one caveat of our results demonstrated that the CA effects in N2 amplitudes were also significantly affected by postconflict slowing for current congruent trials. A possible interpretation of these effects is that people actively and strategically adjust towards a more conservative criterion for ongoing responses whenever they detect a conflict on the previous trial (Botvinick et al., 2001). However, according to an alternative account for this effect, conflict can evoke an orienting response or lapses of attention, which inhibit information processing on the subsequent trial and result in slower and more error-prone performance (Steinborn, Flehmig, Bratzke, & Schroter, 2012; Verguts et al., 2011). Therefore, it calls for further investigation to study the contribution of postconflict slowing in the CA effects.

In the present study, the S-S and S-R conflict effects were not significantly correlated with each other. Previous studies comparing the Stroop and Simon tasks showed the same results (Li et al., 2014; Liu et al., 2010). These results implied that the ability to resolve S-S conflicts was not associated with the ability to resolve S-R conflicts, which further supported the idea that there were distinct mechanisms of S-S and S-R conflict processing. As we and other researchers have argued, there may be a noncentralized,

modular architecture of cognitive control, where separate control resources resolve domain-specific conflicts in parallel (Egner, 2008; Egner et al., 2007).

Our time-frequency results not only confirmed that cognitive control mainly modulated theta power (Cohen & Cavanagh, 2011; Hanslmayr et al., 2008), but also provided evidence indicating the existence of distinct neural mechanisms underlying S-S and S-R conflict processing. We found that both S-S and S-R conflicts mainly enhanced the frontal-central theta band, which played a critical role in conflict processing (Cavanagh, Cohen, & Allen, 2009; Nigbur et al., 2012). Importantly, in our study, additional activity of alpha and beta bands was specifically induced by S-S conflicts. The enhanced alpha power has been observed when people actively restrained their attention to the distracters in order to focus on the targets (Ward, 2003). And the beta band activity has been linked with increased cognitive load (Aulická et al., 2014), task-specific vigilance (Mann, Serman, & Kaiser, 1996), as well as attentional control and response inhibition (Fan et al., 2007; Putman, van Peer, Maimari, & van der Werff, 2010). Therefore, the oscillation of the alpha and beta bands in the S-S conflicts might reflect top-down inhibition on dominant responses.

Our findings from behavioral, ERP, and time-frequency analyses generally support the DO and the domain-specific models, which hypothesize that cognitive control does not operate in a generic way but instead acts locally, specific to the type of conflict. The current results and previous studies (Egner et al., 2007; Funes et al., 2010; Wang et al., 2014) consistently provide empirical support for the modular organization of conflict-driven control in the human brain. Meanwhile, we should caution against making sweeping conclusions. Although a unitary control process would make the resolution of conflicts inefficient, it is unlikely for us to have endless control mechanisms for each potential source of conflict. Evidence from both behavioral studies and neural pattern classification suggests that both domain-general and domain-specific modules may exist in the brain (Akçay & Hazeltine, 2008, 2011; Jiang & Egner, 2014). Some critical questions remain to be answered, for example, when control is specific to a particular conflict, when control is general across different conflicts, and how the boundaries of these control processes are determined. As the evidence regarding conflict control is still limited, further exploration of these questions would help us understand the implementation of control.

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