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RESEARCH ARTICLE

Flanker paradigm contains conflict and distraction factors with distinct neural mechanisms: an ERP analysis in a 2-1 mapping task

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Abstract
Behavioral studies using the flanker 2-1 mapping task suggest that both stimulus and response conflicts contribute to flanker conflict effect. However, both are intertwined with distraction effect. Their underlying neural mechanisms remain unclear. We applied a perceptual flanker 2-1 mapping task to 24 healthy young adults, while the event-related potentials were recorded. The task included stimulus-incongruent (SI), response-incongruent (RI), congruent (CO) and neutral (NE) stimuli. Our reaction time data demonstrated conflict effect, distraction effect and their interaction. Furthermore, the conflict factor successively enhanced the frontal P2 (160–240 ms), the posterior N2pc (200–240 ms), the fronto-central and the right frontal N2b (240–420 ms), and the posterior N2c (320–420 ms). Only the frontal P2 was larger for RI than SI. The distraction factor increased the right N2pc and reduced the left parietal P3b (460–480 ms). Overall, our findings suggested that the flanker conflict involved an early attentional processing of task-relevant and distractive information, and a later processing of conflict evaluation and response inhibition.

Keywords Cognitive control · Flanker conflict · Distraction · 2-1 mapping · Event-related potentials (ERP) · Statistical parametric mapping (SPM)

Introduction

Conflict resolution is one of the most important components of cognitive control (Diamond 2013). Its laboratory studies often use the paradigms of stimulus response compatibility such as Stroop task (Stroop 1935), Simon task (Simon and Rudell 1967), and Eriksen flanker task (Eriksen and Eriksen 1974). The flanker task is a choice reaction time (RT) task about letters or symbols. Typically, the central letter is flanked on both sides by identical letters (e.g., HHHHH, stimulus-congruent, CO), or letters indicating the opposite response (e.g., SSHSS, stimulus-incongruent, SI), or letters requiring no response (e.g., EEHEE, stimulus-neutral, NE). The conflict effect refers to the fact that the response in incongruent condition is slower and/or more erroneous than in CO or NE condition. In addition, a congruent effect may be observed as that the response in CO condition is faster and/or more accurate than in NE condition (MacLeod and MacDonald 2000; Roelofs et al. 2006; Roberts et al. 2010). Obviously, the conflict effect is mixed with the congruent effect if the CO condition is taken as the baseline (Szucs and Soltész 2010), and it is mixed with a distraction effect when NE condition is the baseline, as the flanker also carries distraction information. To date, the neural mechanisms underlying the conflict effect, the congruent or distraction effect, and their interaction effect remain uninvestigated.

According to the dimensional overlap (DO) theory (Kornblum 1994), the conflict effect is derived either from

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the conflict between relevant and irrelevant stimulus dimensions (stimulus–stimulus conflict, SSC), from the conflict between irrelevant stimulus dimensions and relevant response dimensions (stimulus–response conflict, SRC), or from the mixture of SSC and SRC. The DO theory further predicts a two-stage model: SSC mainly involves an early stimulus-encoding stage, while SRC is resolved at a later response-selection stage. By the DO taxonomy, the conflict effects of both the flanker task and the manual Stroop task belong to the SSC type, whereas the conflict effect of the Simon task belongs to the SRC type.

On the other hand, the dual-processes model suggests that conflict resolution involves different processes, depending on the type of stimulus–response (SR) association (de Jong et al. 1994). The first process is a direct and unconditional perceptual-response activation via a long-term-memory SR association (e.g. a right response to a right arrow). The second process is an indirect and conditional selection of relevant (non-spatial) stimulus dimension, and activation of the correct response representation defined by a short-term memory SR association (e.g. a right response to a color). Hence, the difference between these two types of SR association should be considered in conflict research.

However, several studies found that both SSC and SRC contributed to the conflict effect in flanker task (van Veen and Carter 2002) as well as Stroop task (De Houwer 2003; van Veen and Carter 2005). A 2-1 mapping paradigm was applied, in which two stimulus attributes were associated with each response hand. Thus, three conditions were created, stimulus-congruent (CO, two attributes are the same), stimulus-incongruent (SI, two attributes are mapped onto the same response hand), and response-incongruent (RI, two attributes are mapped onto opposite response hands). In this design, the SI condition involves SSC, while the RI condition contains both SSC and SRC. Therefore, identifying these two types of conflicts requires the short-term memory and long-term memory factors to be isolated first.

Two distinct mechanisms have been proposed that the flanker conflict is resolved either by intensified focus of selective attention on the target (Eriksen and St James 1986) or by inhibiting activation of the distracting flanker (Folstein and Van Petten 2008; Pires et al. 2014). Event-related potentials (ERP) technique is suitable for solving these disputes by its excellent temporal precision and by providing neural processing information to delineate different stages of processing.

There are at least three ERP components reported in the literature of flanker tasks, including the frontal P2 component, the fronto-central N2b component, and the centro-parietal P3b component. Firstly, Both Korsch et al. (2016) and Kałamała et al. (2018) found that the basic or modified arrows flanker task with equiprobable congruent and incongruent conditions elicited a larger frontal P2 in incongruent trial than in congruent trials. The P2 component (also known as P2a) typically occurs over frontal or fronto-central regions with the peak around 150–250 ms post-stimulus (Luck and Hillyard 1994a, b). It was reported to be increased only in response to the target (Potts 2004). The above two flanker studies thus interpreted the enhanced P2 component as reflecting greater involvement of selective attention during processing incongruent trials. However, due to the stimuli design, both the basic and modified arrows flanker tasks where the enhanced P2 were observed could not separate the role of SSC and SRC in the P2 effect.

Following the frontal P2 component, a larger fronto-central N2b occurring about 200–380 ms after stimulus onset in conflict trials were more commonly revealed in studies of flanker conflict (Folstein and Van Petten 2008; Kim et al. 2011; Larson et al. 2014). The neural generator of this N2b component was demonstrated to be medial frontal cortex, especially the anterior cingulate cortex (ACC), and was assumed to reflect conflict monitoring and response inhibition processes (van Veen et al. 2001; Neuhaus et al. 2007; Folstein and Van Petten 2008). When investigating the influence of SSC and SRC on the N2b component, there were great inconsistencies in previous studies. Forster et al. (2011) proposed that the N2b (290–330 ms) just indicated SSC as its amplitude increased with stronger flanker incompatibility, while van Veen and Carter (2002) found that the N2b (340–380 ms) only reflected SRC. Meanwhile, Wendt et al. (2007) showed that significant N2b (240–280 ms) was elicited by both SSC and SRC, and there was no significant amplitude difference between SSC and SRC. However, other studies reported that the N2b evoked by SRC was larger or later than the N2b evoked by SSC (Nigbur et al. 2011; Donohue et al. 2016). Furthermore, some findings obtained from typical letter or arrow flanker tasks even challenged the notion that the N2b is a valid index of conflict processing: the N2b effect (220–300 ms) increased with less behavioral interference when incongruent trials were more frequent (Bartholow et al. 2005; Tillman and Wiens 2011). Based on their novel finding, Tillman and Wiens (2011) suggested that the N2b might index attentional control or inhibition process as an alternative to the conflict-monitoring theory (Botvinick et al. 2004). It must be noted that their flanker task mixed SSC and SRC. Another challenging finding came from a recent study by McKay et al. (2017). They revealed that an early-enhanced N2b was shown in both the flanker conflict trials and the difficult trials of a non-conflict control task, where a later negativity named Ninc was larger only for the flanker conflict trials. The early N2b effect, together with the N2b effect found in previous literature, were then discussed as including both conflict and difficulty effect, and reflecting additional allocation of attentional resources. The inconsistencies about the fronto-central N2b in the above studies are partly due to the less differentiation between the short-term memory SR association and the long-term memory SR association, between the SSC and SRC, or between the conflict factor and the distraction factor.

Fewer studies investigated the P3b component with the flanker task than the N2b component. Some research revealed conflict adaptation effect in the P3b component (Neuhaus et al. 2010; Clayson and Larson 2011a, b). For example, Neuhaus et al. (2010) applied a cued arrows flanker task and identified a frontal P3a amplitude increment and parietal P3b amplitude decrement in incongruent trial following a previous incongruent trial. They interpreted that the modulation of the P3a and P3b amplitudes reflected response inhibition and visual target detection respectively. However, other studies found that P3b effect was dissociated with behavioral RT and was not specifically related to task type (flanker conflict, Stroop conflict, or non-conflict task) or the amount of response conflict (Donohue et al. 2016; McKay et al. 2017). These data, in contrast with the conflict adaptation studies, indicated that P3b was not sensitive to conflict information. Therefore, the relationship between P3b and conflict processing was still unclear, and the different influence of SSC and SRC on P3b was not explored directly.

In addition to the above ERP components found in flanker conflict task, a novel N2pc (N2-posterior-contralateral) component was proposed to be involved in conflict processing though in other conflict tasks. The N2pc component is usually characterized by a greater negative deflection occurring 200–300 ms after stimulus onset at left and right posterior scalp sites contralateral to the attended object in the visual scene (Luck and Hillyard 1994a, b). N2pc is acknowledged to reflect multiple consequences of focusing attention onto a lateralized object. For example, in additional singleton paradigm, a lateral salient distractor often evoked an N2pc, indicating attentional capture by the distractor. It seems that the N2pc shows laterality under some circumstances. A left lateralized N2pc was found by using the word discrimination task (Eimer 1996) or the color category task (Liu et al. 2009). Meanwhile, a right lateralized N2pc was observed by using a dual-stream rapid serial visual presentation (RSVP) task (Verleger et al. 2011, 2013; Śmigasiewicz et al. 2015). Several conflict research also observed N2pc effect. In a series of studies used a Simon-like task with arrow position and direction as irrelevant dimensions, N2pc was found to be modulated by conflict and be related with allocation of attentional resources to the target stimulus (Cespon et al. 2013a, b). However, whether the N2pc was also involved in flanker conflict processing is still unanswered.

Since these ERP components were elicited by using flanker tasks with numerous variations, they seem to reflect a host of different processes such as attention allocation, conflict detection and evaluation, response selection and inhibition. One way to clarify the functional significance of these ERP components of the flanker task is to dissociate the distraction and conflict factors and to separate SSC and SRC in one single task. A perceptual flanker task without letters or arrow symbols was favored to reduce the confounding from semantic information, or the long-term memory SR association.

In current study, we applied a color flanker 2-1 mapping task, and introduced the response-irrelevant neutral (NE) stimuli in addition to the RI, SI, and CO stimuli in previous flanker 2-1 mapping task. In our flanker task, the stimulus was colored circle target surrounded by colored ring flanker, which was not a traditional flanker stimulus (Wendt et al. 2014; Li et al. 2018; Beaton et al. 2018). It was designed to balance horizontal and vertical directions (Weeks et al. 1995), and to reduce semantic information and long-term memory SR induced by letters and arrows flankers. The conflict factor included two levels, with the RI and SI as the conflict level, and the NE and CO as the non-conflict level. The distraction factor also included two levels, with the RI and NE as the high distraction level, and the SI and CO as the low distraction level. Therefore, we tried to investigate the behavioral and ERP effects elicited by the conflict factor and the distraction factor.

Materials and methods

Participants

Twenty-four healthy undergraduate and graduate students (12 women; age range: 22–30 years; mean age: 25.54 years, SD: 2.19 years) served as paid participants. All were right-handed and had normal or corrected-to-normal vision without color blindness. None had a history of neurological or psychiatric disorders. Participants were fully informed about the schedule and goals of the study and gave written informed consent in accordance with procedures approved by the Medical Ethics Committee of Nanfang Hospital, Southern Medical University.

Experimental procedure

Participants completed the flanker 2-1 mapping task in a sound-attenuated, dimly lit chamber. The stimuli against a black background were presented on the center of a 17-in. computer monitor connected to a ThinkPad notebook. The distance between the screen and the participants was 120 cm. Each stimulus consisted of an inner circle (target) and an outer ring (flanker) (Fig. 1). The diameter of the inner circle was 1.7 cm (0.8° in visual angle), and the insider and outsider diameters of the ring were 2.6 cm (1.2°) and 3.6 cm (1.7°) respectively. The colored circle stimuli here did not contain semantic information that is present in letters and numbers used in traditional flanker task. Participants were instructed to press a left or right button on a gamepad with the corresponding hand as quickly as possible according to the color of the target (inner circle) of each stimulus.

In the flanker 2-1 mapping task, four colors on a black background were mapped on two responses and their RGB values are (red: 255, 0, 0), (yellow: 255, 255, 0), (green: 0, 255, 0), (blue: 0, 0, 255), and (black: 0, 0, 0). Two colors (red and yellow) required a left-hand response, whereas the other two (green and blue) required a right-hand response. Thus, such design yielded three conditions, namely (1) a congruent (CO) condition with identical target and flanker, (2) a stimulus-incongruent (SI) condition where target and flanker differed in color but required the same response hand, and (3) a response-incongruent (RI) condition with target and flanker differed in color and required different response hands. In addition, a neutral condition (NE) was added where the flanker was gray with RGB values (192, 192, 192).

After a practice block helping participants to get familiar with the task, 320 trials were presented in eight blocks of 40 trials, yielding 80 trials per condition. During each trial, the stimulus was presented for 500 ms with an inter-trial interval of 1500 ms. All trials were presented pseudo-randomly during each block, making sure that three successive trials of the same type were not presented.

Electroencephalogram (EEG) recordings and pre-processing

The EEG was continuously recorded at a sampling rate of 1000 Hz with a 19-channel EEG amplifier (the Symtop

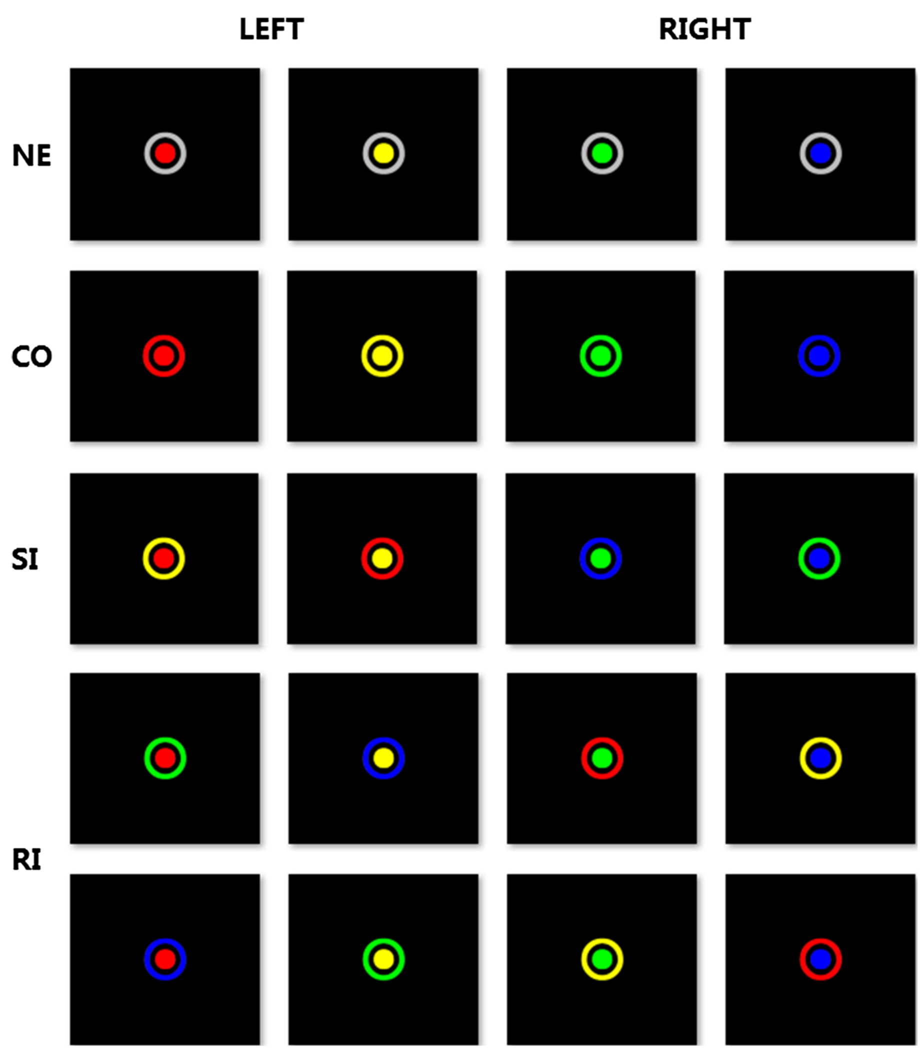

Fig. 1 Illustration of task conditions. Subjects were required to respond to the color of the central circle and select a left or right response key. Four different conditions including the neutral (NE), congruent (CO), stimulus incongruent (SI), and response incongruent (RI) stimuli were presented in randomized order during the task. (Color figure online)

Instrument®). The recording bandwidth was 0.5–100 Hz. The international 10–20 system (FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz, and Pz) was used with linked earlobes as the reference. The electrode impedances were kept below 10 kΩ.

Before ERP averaging, ocular, muscular, and any other artifacts within the EEG signal were detected at the threshold of ± 70 μV, and the EEG signal was automatically corrected via a principal component analysis method (Lins et al. 1993a, b). Only correct response trials were averaged. The averaged ERP epochs were extracted from the ongoing EEG, including 100 ms prior to stimulus onset and 600 ms after stimulus onset. The baseline ERP measurement was the mean amplitude of a 100-ms pre-stimulus interval.

Data analyses

Behavioral analyses

The mean RTs of correct response and accuracy were calculated. The results of the RT and the accuracy were submitted to a two-way repeated measures analysis of variance (ANOVA) using the SPSS 22.0 software. The two within-subject factors were conflict (conflict SI/RI vs. non-conflict CO/NE) and distraction (high distraction RI/NE vs. low distraction SI/CO). Effect sizes were showed using partial eta square (η_p^2) and Cohen's *d*. Two-tailed paired *t* tests were applied for pairwise comparisons of behavioral data.

ERP analyses

The ERP components and effects were chosen based on previous literature about flanker conflict processing, including the frontal P2, the posterior N2pc, the fronto-central N2b/N2c, and the P3b. To isolate ERP components, we inspected the grand-averaged ERP waveforms to find prominent differences between experimental conditions. Four ERP components were visually identified: (a) a frontal P2 component (160–240 ms), (b) a posterior N2pc component (200–240 ms), (c) a fronto-central N2b component and a posterior N2c component (240–400 ms), and (d) a parietal P3b component (400–560 ms).

Using statistical software for ERP spatiotemporal analysis developed in our lab, ERP data at each time-point for all channels (electrode-wise) were submitted to two-way repeated measures ANOVA. The two within-subject factors were conflict (conflict SI/RI vs. no-conflict CO/NE) and distraction (high distraction RI/NE vs. low distraction SI/CO). Two-tailed paired *t* tests were applied for pairwise comparisons. A multichannel time series of *F*-values/*t*-values were used to generate topographical maps via an interpolation method relevant to a generalized cortical imaging technique (Zhou et al. 1998, 2004). The statistical parametric mapping (SPM) of *F*-values/*t*-values will be referred to as SPM(*F*)/SPM(*t*) hereafter. The topographical maps series were derived from the averaged *F*-values/*t*-values within a fixed 20 ms windows and a sliding step of 20 ms without overlapping data. The significance threshold was set to .05 for all analyses.

Results

Behavioral performance

Table 1 presented descriptive statistics of the RT and the accuracy. Table 2 showed the results of the two-way repeated measures ANOVA. No significant effects on the accuracy were found; but the interaction and main effect of conflict and distraction factors of the RT were all significant. Follow-up pairwise comparisons revealed several significant effects, including the SRC effect (RI–SI): $t(23) = 6.30$, $p < .001$, $d = 1.286$; the SSC effect (SI–NE): $t(23) = 3.18$, $p < .004$, $d = .649$; and a distraction rather than a congruent effect (CO–NE): $t(23) = 2.18$, $p < .039$, $d = .445$.

The ERP waveform and component analysis

Figure 2 depicted the grand averaged ERP waveforms (from − 100 to 600 ms) of nine representative electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) in the fronto-centro-parietal regions. The Supplementary Figure 1 showed the grand averaged ERP waveforms of all 19 electrodes.

Significant effects were demonstrated for the frontal P2 (160–220 ms), N2pc (200–240 ms), N2b/N2c (240–400 ms), and P3b (400–560 ms) components. Table 3 listed significant average statistics (i.e., *F*-value/*t*-value, η_p^2, and *d*) of P2 and N2pc at prominent electrodes (Fz, F3, O2, T6, T4, P4 and P3) within 20 ms time window without overlapping data. Table 4 listed significant average statistics (i.e., *F*-value/*t*-value, and η_p^2, and *d*)of N2b, N2c and P3b at prominent electrodes (Cz, C4, F4, T5 and P3) within 20 ms time window without overlapping data.

Spatiotemporal pattern of ERP: SPM(*F*) and SPM(*t*)

Figure 3 showed the spatiotemporal patterns of SPM(*F*) (160–560 ms) derived from the two-way repeated measures ANOVA. Each map was interpolated from the average *F*-values within the fixed 20 ms time window, and the bright yellow bin of the color scale corresponded to the

Table 1 Behavioral performance summary (mean ± standard deviation) (N = 24)

	NE	CO	SI	RI
Reaction time (ms)	516.52 ± 58.19	526.73 ± 69.41	538.13 ± 73.66	561.25 ± 75.20
Accuracy (%)	93.96 ± 5.51	93.13 ± 7.63	92.19 ± 6.05	94.17 ± 4.46

Table 2 Two-factor repeated measures ANOVA of behavioral data (N = 24)

	Reaction time			Accuracy		
	$F_{(1,23)}$	P	η_p^2	$F_{(1,23)}$	P	η_p^2
Conflict: (RI + SI)/(CO + NE)	21.055	0.000	0.478	0.160	0.693	0.007
Distraction: (RI + NE)/(SI + CO)	7.293	0.013	0.241	3.003	0.096	0.115
Interaction: (RI + CO)/(SI + NE)	33.438	0.000	0.592	0.347	0. 561	0.015

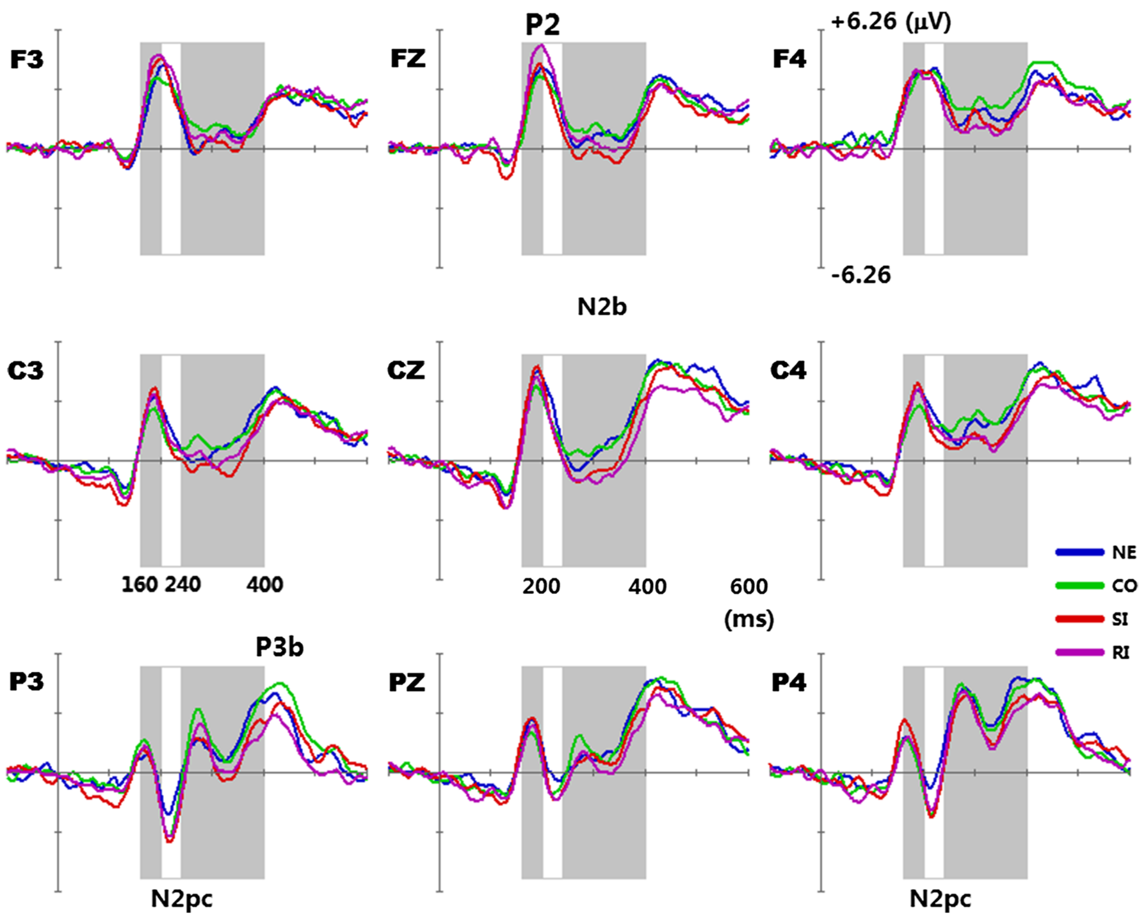

Fig. 2 Grand average ERP waveforms (from − 100 to 600 ms) are shown for 9 representative electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) in the fronto-centro-parietal regions across all trial types, from the 24 subjects. The blue, green, red and purple traces correspond to group average ERP of the neutral (NE), congruent (CO), stimulus-incongruent (SI) and response-incongruent (RI) conditions respectively. The baseline ERP measurement is the mean amplitude of 100 ms pre-stimulus interval. (Color figure online)

.05 significance threshold: $F(1, 23) = 4.28$. The white dots represented the electrode sites with significant effects.

As shown in Fig. 3, it was found that, (a) The conflict factor enhanced successively the frontal P2, the right occipito-temporal and left parietal N2pc, the fronto-central N2b, the right frontal N2b, and the posterior N2c. (b) The distraction factor involved the medial-frontal P2, the right occipito-temporo-parietal N2pc and the left parietal P3b consecutively. (c) The interaction effect was present at the left fronto-temporo-parietal, the fronto-central, and the right frontal regions only during 260–280 ms after stimulus onset.

Figure 4 presented the spatiotemporal patterns of SPM(t) (160–560 ms) derived from the pairwise

Table 3 Significant P2 and N2pc effects (sites) within 20 ms time window (N = 24)

Effects	Pairwise comp.	F(1,23)/p t(23)/p ES/WO	P2 (Fz)		P2 (F3)		N2pc (O2)		N2pc (T6)		N2pc (T4)		N2pc (P4)		N2pc (P3)	
			Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO
Interaction		F/p														
		η_p^2/WO														
Conflicts		F/p	4.34	.048	9.77; 8.33	.004; .008	10.91	.003	5.68	.025					8.93	.006
		η_p^2/WO	.16	180	.30; .26	170; 180	.32	200	.19	200					.28	220
Distraction		F/p	6.88	.015			4.36	.048	6.75	.016	4.04	.056	5.75	.025		
		η_p^2/WO	.23	200			.16	200	.23	200	.15	198	.19	200		
Distracting	CO–NE	t/p					− 2.21	.037	− 2.38	.025	− 2.29	.031	− 2.52	.019		
		d/WO					.451	200	.485	200	.467	198	.514	200		
Congruent	NE–CO	t/p														
		d/WO														
Stimulus	SI–NE	t/p			2.20	.038	− 2.89	.008	− 2.99	.006			− 2.08	.048	− 2.22	.036
		d/WO			.449	170	.589	200	.610	200			.424	200	.453	220
Conflict	SI–CO	t/p														
		d/WO														
Response conflict	RI–SI	t/p	2.33	.028	2.29	.031										
		d/WO	.475	200	.467	215										
Double	RI–NE	t/p			2.13	.044	− 2.58	.016							− 2.21	.037
		d/WO			.434	170	.526	200							.451	220
Conflicts	RI–CO	t/p	2.19	.038	2.24	.035										
		d/WO	.447	180	.457	180										

NE: neutral, CO: congruent, SI: stimulus-incongruent, RI: response-incongruent, ES: effect size, WO: window onset

Table 4 Significant N2b, N2c and P3b effects (sites) within 20 ms time window (N = 24)

Effects	Pairwise comp.	F(1,23)/p t(23)/p ES/WO	N2b (Cz)		N2b (Cz)		N2b (F4)		N2b (C4)		N2c (T5)		N2c(P3)		P3b (P3)	
			Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO	Stat.	p/WO
Interaction		F/p									9.04	.006				
		η_p^2/WO									.28	260				
Conflicts		F/p	6.81	.015	16.74	.000	4.96	.036	13.79	.001			9.57	.005		
		η_p^2/WO	.23	260	.42	320	.18	260	.37	320			.29	380		
Distraction		F/p													13.1	.001
		η_p^2/WO													.36	460
Distracting	CO–NE	t/p														
		d/WO														
Congruent	NE–CO	t/p									– 2.30	.030			– 2.15	.042
		d/WO									.469	260			.438	460
Stimulus	SI–NE	t/p			– 2.42	.023										
		d/WO			.493	320										
Conflict	SI–CO	t/p	– 2.26	.033			– 2.14	.043	– 2.23	.035	– 2.99	.006				
		d/WO	.461	260			.436	260	.455	320	.610	260				
Response conflict	RI–SI	t/p														
		d/WO														
Double	RI–NE	t/p			– 3.02	.006			– 2.09	.047			– 2.53	.018		
		d/WO			.616	320			.426	320			.516	380		
Conflicts	RI–CO	t/p	– 2.31	.030	– 2.29	.031	– 2.19	.038	– 2.31	.030			– 2.46	.021	– 2.67	.013
		d/WO	.471	260	.467	320	.447	260	.471	320			.502	380	.545	460

NE: neutral, CO: congruent, SI: stimulus-incongruent, RI: response-incongruent, ES: effect size, WO: window onset

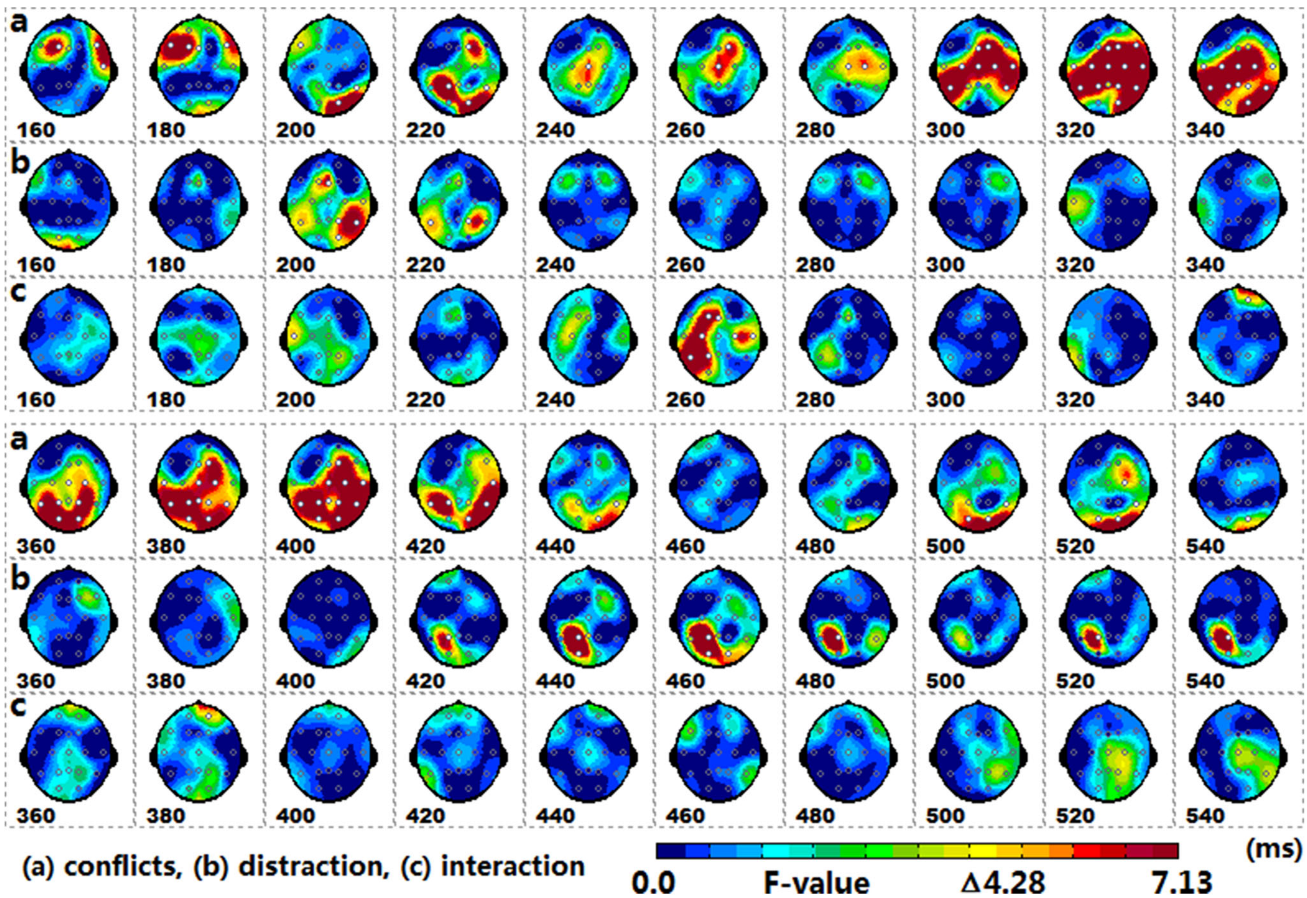

Fig. 3 The spatiotemporal patterns of SPM(F) (160–560 ms) is derived from the two-way (conflict: RI and SI, CO and NE; distraction: RI and NE, CO and SI) repeated measures ANOVA: **a** the conflict effect, **b** the distraction effect and **c** the interaction effect. Each map is interpolated from the average F-values within window length of 20 ms, the white dots represent the sites with significant effects. For the spatiotemporal patterns of SPM(F), the bright yellow of the color scale corresponds to the .05 significance threshold: $F(1, 23) = 4.28$. NE: neutral, CO: congruent, SI: stimulus-incongruent, RI: response-incongruent. (Color figure online)

comparisons between experimental conditions: (a) (CO–NE), (b) (SI–NE), (c) (RI–NE), (d) (NE–CO), (e) (SI–CO), (f) (RI–CO) and (g) (RI–SI). Each map was interpolated from the average t-values within the fixed 20 ms time window, and the white dots represented the sites with significant effects. Moreover, the .05 significant threshold $t(23) = \pm 2.07$ were pointed by the triangles at the two ends of the color scale.

Discussion

By employing the flanker 2-1 mapping task and ERP technique, we aimed to dissociate the conflict and distraction factors inherently in the flanker task, and to reveal the neural mechanism of stimulus and response conflict of short-term memory.

Behavioral performance

For the RT data, the interaction and main effects of the conflict and the distraction factors were all significant. Further pairwise comparison analysis showed both the SSC effect (SI–NE) and the SRC effect (RI–SI) were significant, which was consistent with previous RT findings using similar tasks (van Veen and Carter 2002; Wendt et al. 2007), and supported the DO theory that the conflict should be divided into SSC and SRC. However, the significant RT difference between the two conditions (RI–SI) may also be caused by competition between the two parallel and overlapping processes (SSC and SRC) rather than the difference between the two serial processes. The neural processing information provided by our ERP results helped to clarify the relationship between these SSC and SRC processes. On the other hand, the RT of the CO condition was significantly longer than that of the NE condition, suggesting a distraction effect rather than a congruent effect (Roelofs et al. 2006; Roberts et al. 2010).

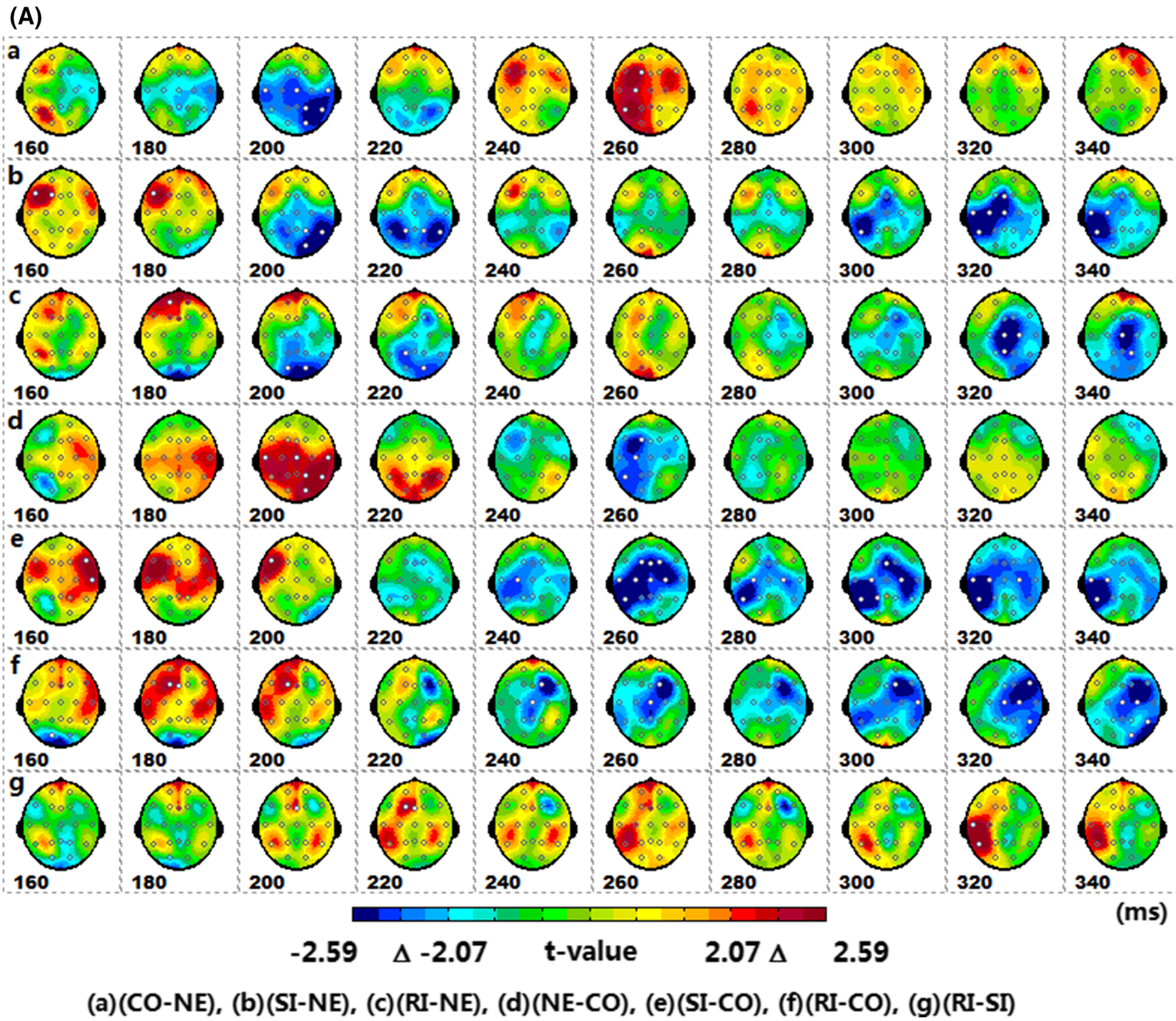

Fig. 4 The spatiotemporal patterns of SPM(t) from 160 to 360 ms (**A**) and from 360 to 560 ms (**B**) are derived from the pairwise comparisons between the conditions (NE, CO, SI, RI): (a) (CO–NE), (b) (SI–NE), (c) (RI–NE), (d) (NE–CO), (e) (SI–CO), (f) (RI–CO) and (g) (RI–SI). Each map is interpolated from the average t-values within window length of 20 ms, the white dots represent the sites with significant effects. For the spatiotemporal patterns of SPM(t), the colors beyond the .05 significant threshold $t(23) = \pm 2.07$ at the two ends of the color scale represent significant regions. Note that the spatial pattern of (CO–NE) and that of (NE–CO) are mutually opposite mirror images. NE: neutral, CO: congruent, SI: stimulus-incongruent, RI: response-incongruent. (Color figure online)

The conflict effect of ERP

The enhanced frontal P2, bilateral N2pc, the N2b over the right and central frontal regions, and the posterior N2c were observed in conflict conditions (SI and RI) than non-conflict conditions (CO and NE), reflecting neural correlates of conflict processing.

The larger frontal P2 effect shown in the present study was rarely reported in previous studies using flanker tasks. A recent published paper employed a basic version of the arrow flanker task to a large-sample of participants, and reported a frontal P2 component (200–320 ms after stimulus onset) larger for incongruent than congruent trials (Kałamała et al. 2018). Such P2 effect was interpreted as indexing greater involvement of selective attention during processing incongruent trials. Similar P2 increment in incongruent trials was also found in the combined flanker and Simon task (Korsch et al. 2016). Kałamała et al. (2018) discussed the possible reasons for the P2 effect observed in their study. One of the reasons was that their stimuli were randomly presented above or below the fixation and had a rather small visual angle, which might increase the conflict and task demands and lead to the enhanced P2 effect. However, in typical flanker experiments, the conflict might be too small to induce the P2 effect. Thus, it suggested that the frontal P2 effect was sensitive to the amount of conflict. The latency (i.e., 160–220 ms) and scalp distribution (i.e., dorsolateral frontal region) of the frontal P2 effect in our study were consistent with the study by Kałamała et al. (2018). It was possible that the amount of the conflict in our flanker task was also larger than typical flanker tasks in previous studies, leading to the observed enhancement of frontal P2 component. Post hoc analysis further showed significant effect when comparing SI and RI separately with the non-conflict condition, including RI and NE (F3), SI and NE (F3), and RI and CO (Fz and F3). These results suggested that both SSC and SRC resolution required increased attentional selection.

The second conflict-related ERP effect was shown at posterior brain regions. The conflict trials evoked a larger bilateral posterior N2pc in relative to non-conflict trials. In view of the close relationship between N2pc and attentional processing (Luck and Hillyard 1994a, b), it is possible that the increased N2pc reflect consequence of more attentive target processing in conflict trials. The current data, together with the finding that contradictory irrelevant information reduced the N2pc in a Simon-type task (Cespon et al. 2013a, b), further confirmed the involvement of attentional process when confronted with conflict information.

With regard to the fronto-central N2b effect related with conflict factor, it was present in several brain regions and during three different time windows, implicating different neural mechanism. Firstly, the earlier fronto-central N2b (Cz; 240–420 ms) was larger in conflict conditions (RI and SI) than non-conflict conditions (NE and CO). This data was consistent with previous findings that the N2b enhancement reflected both SSC and SRC (Wendt et al. 2007; Nigbur et al. 2011, 2012; Donohue et al. 2016), and indicated the involvement of the anterior cingulate cortex during conflict evaluation (van Veen and Carter 2002; Sohn et al. 2007; Kim et al. 2011).

The right frontal N2b effect (F4 and C4 sites; 260–360 ms, 280–420 ms) followed the earlier fronto-central N2b effect. Previous work has suggested that a right frontal response-inhibition mechanism is critical for the generation of the right frontal N200 (Pliszka et al. 2000). Our data were also in line with the finding that right prefrontal areas were involved during demanding response conflict situations using a letters flanker 2-1 mapping task and time–frequency analysis of ERP (Nigbur et al. 2012). In addition, the meta-analysis of fMRI studies on flanker paradigm suggested that the conflict resolution involved the right frontal area (Nee et al. 2007; Cieslik et al. 2015), which was demonstrated to be a part of the right-lateralized response-inhibition network (Zheng et al. 2008; Verbruggen and Logan 2008; Sharp et al. 2010; Aron 2011; Bari and Robbins 2013). Thus, the enhanced right frontal N2b in our study suggested that resolving conflict required some response inhibition process.

The last N2 effect was the increment of the posterior N2c (300–440 ms) in conflict conditions (mainly the RI) than non-conflict conditions. It may reflect the degree of attention required for processing of stimuli context and features in bilateral occipito-parietal regions (Suwazono et al. 2000; Folstein and Van Petten 2008). In the RI-minus-CO comparison, the left parietal N2c effect and the right-frontal N2b effect co-occurred (380–420 ms), suggesting that the N2c effect also contributed to the inhibition of competitive motor instruction.

In addition, the interaction of conflict and distraction factors was shown as the left fronto-temporal N2 effect (F3, C3, and T5 sites; 260–280 ms). It actually resulted from the pairwise comparisons involving both the SI and the NE stimuli: (SI–CO) and (NE–CO). This result was in line with ERP studies of the categorical perception of color (Liu et al. 2009, 2010; Lu et al. 2014; He et al. 2014): an N2 component (200–350 ms) distributed in the left fronto-central region reflected post-perceptual process. However, future studies are required to clarify why the RI stimuli lack this effect (RI–CO). One possible reason is that the double conflict load of the RI stimuli may involve more attention resources that could otherwise be used for color classification processing.

The distraction effect of ERP

The distraction factor involved the medial-frontal P2, the right posterior N2pc and the left parietal P3b successively.

The medial-frontal P2 was enhanced by the distraction factor. Post hoc analysis revealed that the P2 was larger in RI condition than in SI condition as well as in CO condition, while no significant difference was found between NE and CO conditions. The current data helped to understand the similar P2 enhancement effect in previous studies where SSC and SRC were mixed (Kałamała et al. 2018). The difference between the P2 in RI and SI condition indicated additional attention was needed to resolve the SRC than SSC, while the attentional requirements by NE and CO conditions were similar in this stage of processing. Combined the conflict-related frontal P2 effect and the distraction-related frontal P2 effect, it suggested that attentional resources was first engaged in coarse conflict resolution, and then in fine distraction suppression.

The distraction factor also enhanced the right posterior N2pc. Previous studies found that N2pc occurred earlier at the right hemisphere than the left hemisphere in a dual-stream RSVP task (Verleger et al. 2011). Such right-hemisphere advantage was also replicated with stimuli presented at vertical midline, and reflected right-hemisphere advantage in attentional selection (Verleger et al. 2013; Śmigasiewicz et al. 2015). The right N2pc effect in our study was in accordance with these studies. It was present at an earlier stage than the conflict-related bilateral N2pc effect. Thus, the observed right N2pc effect indicated the processing consequence of attentional selection of the current stimuli. During post hoc analysis, when comparing CO with NE condition (CO-NE), a negative-going N2pc effect during 200–220 ms was observed as shown in Fig. 4A(a). That is, it was the CO stimuli with colored flanker, in relative to the NE stimuli with gray and task-irrelevant flanker that elicited the earlier right N2pc effect. Similarly, when comparing with the NE stimuli, both SI stimuli and RI stimuli elicited the earlier N2pc effect seen in Fig. 4A(b–c). However, when compared with CO stimuli with colored flanker, SI and RI stimuli with colored flanker did not evoke any N2pc effect [see Fig. 4A(e–f)]. These data indicated that the earlier and more right lateralized N2pc effect reflected the consequence of attention to the salient flanker distractor with color.

Besides, as shown in Table 3, the CO-elicited right N2pc in relative to NE condition involved more channels than SI-elicited right N2pc, and the later invovled more channels than RI-elicited right N2pc. Although such results seemed contrary to our expectation at first glance, the pattern coincided with the pattern seen in frontal P2 effect, though in a reversed direction. The frontal P2 amplitude showed no significant difference between CO and NE conditions at frontal sites, and it was larger in SI condition than NE condition (see Fig. 4A(a, b) and Table 3). Moreover, the frontal P2 was even larger in RI in comparison

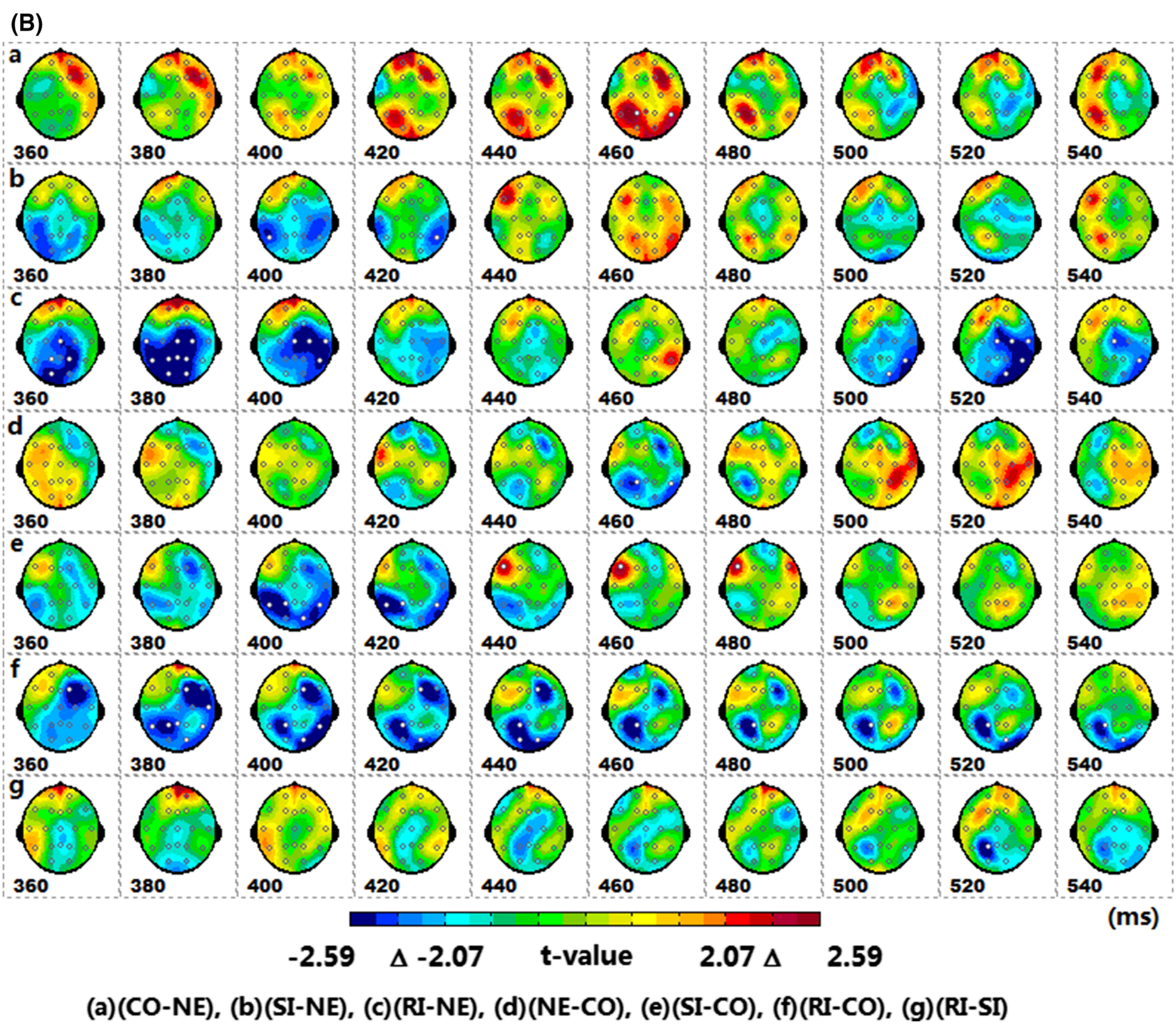

Fig. 4 continued

with SI condition (see Fig. 4A(g) and Table 3). A previous study about N2pc used a visual search task, and argued that participants can exert top-down control to prevent distraction by salient stimuli when activity in frontal cortex is high (McDonald et al. 2013). Such speculation was confirmed by a later transcranial direct current stimulation (tDCS) study. It was reported that the brief application of anodal tDCS centered over the F3 and F4 sites reduced the attentional capture effect caused by a salient distractor (Cosman et al. 2015). The current data was consistent with these studies, by showing that when the P2 in frontal cortex was larger, the N2pc indexing attentional capture by the colored flanker distractor was smaller. Specifically, RI condition with the largest frontal P2 was accompanied with the least channels of significant N2pc, SI condition with the secondly largest frontal P2 was accompanied with less channels of N2pc, while CO condition without the frontal P2 effect was accompanied with the most channels of N2pc. Thus, it seemed that, in the present flanker task design, SI and RI condition involved more top-down control than CO condition.

We argued that these N2pc effects might be regulated by the top-down attention mechanism reflected by the frontal P2 effect. The results of the visual search experiment on primates has revealed that the inhibition of frontal neurons precedes the inhibition of the visual cortex (Cosman et al. 2018). In the future, connectivity-based ERP analysis will further shed light on this point. At present, the evidence is mainly from neuroimaging: visual cortex was highly connected to parietal and prefrontal cortex while doing visual attention task (Parhizi et al. 2018). Moreover, activity of the right temporo-parietal junction of the right ventral attention network (rVAN) was suppressed by the dorsal attention network (DAN) (Shulman et al. 2003, 2007; Todd et al. 2005), which had been interpreted as a filtering mechanism during a focused attention state to protect goal-driven behavior from irrelevant distractors. The right N2pc may reflect the activation of the rVAN since both functions are to reorient attention towards salient stimuli. This requires source analysis to provide further evidence.

Finally, the left parietal P3b effect (420–560 ms) was significantly influenced by the distraction factor. The P3b was smaller in the RI (420–560 ms), the SI (400–440 ms) and the NE (460–480 ms) trials in relative to the CO trials. Several previous studies reported reduced P3 in incongruent trials of the flanker task (Doucet and Stelmack 1999; Neuhaus et al. 2007, 2010). These authors commonly interpreted the reduced P3b as the result of task difficulty. That is, when task difficulty is high, P3b amplitude is attenuated. Although the attenuated P3b in SI and RI conditions in current data might be explained as influenced by task difficulty, the reduced P3b in NE condition was inconsistent with this interpretation, since the incongruent information was absent and the RT in this condition was shortest. In a review about P3 (Kok 2001), it discussed that decreased P3b amplitude was found as a function of increase of memory load, and it reflected depleted resources due to increasing demands of memory maintenance. In the present study, when the CO stimuli were presented, participants only needed to activate and maintain a single stimulus–response mapping in order to respond correctly. In contrast, when NE, SI and RI stimuli were presented, participants had to activate and maintain two stimulus–response mappings before responses. For example, if the stimulus was a NE stimulus with a red central circle and a gray ring flanker, it was possible that the 'red-left press' mapping and the 'gray-no press' mapping were activated simultaneously. The same situation was applied for SI and RI stimulus. Therefore, according to Kok (2001), the attenuation of P3b in NE, SI and RI conditions in the current study may reflect the influence of higher memory load of stimulus–response mapping in comparison with CO condition.

A preliminary two-stage model of flanker conflict processing

Based on present behavior and ERP data, as well as results from previous studies, a preliminary model about cognitive mechanisms underlying flanker conflict processing was proposed. It may reconcile discrepancies in literature about the role of selective attention (Eriksen and St James 1986) versus conflict evaluation and inhibition (Folstein and Van Petten 2008; Pires et al. 2014) during flanker conflict processing, and help to extend the understanding of the SSC and SRC taxonomy based on the DO theory (Kornblum 1994).

Specifically, we proposed that two successive cognitive processes or stages were required to complete the flanker task. The first stage was mainly related with top-down attentional control from frontal cortex induced by general task demands due to the conflict and distraction, and the second stage was associated with conflict evaluation and inhibition from fronto-central cortex. The enhanced frontal P2 in conflict trials found in our study and recent studies (Korsch et al. 2016; Kałamała et al. 2018), as well as the enhanced earlier frontal N2 common for both the incongruent trial in flanker task and for the difficult trials in a non-conflict task (McKay et al. 2017), provided evidence for the attentional selection in conflict task processing. Accordingly, the bilateral N2pc effect evoked by SI and RI conditions in the present study, together with the finding that the Simon-like conflict task involved N2pc (Cespon et al. 2013a, b), further confirmed the involvement of attentional process when confronted with conflict information. In addition, this attention-related stage is also the stage at which SRC differed from SSC, since the present ERP data showed that the frontal P2 was larger in RI than SI. The DO processing model predictes that SSC and SRC involved distinct processing stages. That is, SSC is resolved at an early stimulus-processing stage, while SRC is resolved at a later response-production stage (Kornblum and Lee 1995). Therefore, our model is different from the DO processing model by showing that the difference between SSC and SRC is at a similar early-processing stage. After the first stage of attentional processing, a second stage started to evaluate and then inhibit conflict information. In our study, both SI and RI stimuli elicited a larger fronto-central N2b, and then a larger right lateralized frontal N2b. An enhanced fronto-central N2b in conflict trials was a classic index of conflict monitoring between target and flanker in incongruent stimuli in a number of studies (Folstein and Van Petten 2008; Donohue et al. 2016). When the conflict was evaluated and an irrelevant response alternative was triggerd by the flanker, a response inhibition mechanism was necessary for resolving the conflict. The increased right frontal N2b effect may reflect such inhibitory process.

Limitations

We proposed in the present study that the frontal P2 and the posterior N2pc covaried with each other in an opponent way when processing conflict information. Although this observation was consistent with related studies, connectivity analysis still needs to be performed to further clarify this issue. Besides, the two-stage model of flanker conflict processing is only preliminary, and future studies are expected to provide additional support. Finally, the sparse electrode sampling used in the present study is difficult to provide precise source estimation. Further source localization studies with high-density EEG sensors will improve our understanding of neural cognitive networks underlying cognitive control.

Conclusion

The present study has revealed that both stimulus conflict (SSC) and response conflict (SRC) of short-term memory enhanced the frontal P2, the bilateral posterior N2pc, the fronto-central N2b, the right frontal N2b and the posterior N2c in comparison with non-conflict congruent and neutral trials. The unique difference between SSC and SRC was the increased frontal P2 effect, where it was larger for SRC. The distraction factor increased the right N2pc and reduced the left parietal P3b. Taken together, the current findings indicated that the flanker conflict involved an early attentional mechanism about task-relevant and distractive information processing, and a later mechanism of conflict evaluation and response inhibition.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

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