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Temporal and spectral profiles of stimulus–stimulus and stimulus–response conflict processing

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ABSTRACT

The ability to detect and resolve conflict is an essential function of cognitive control. Laboratory studies often use stimulus–response-compatibility (SRC) tasks to examine conflict processing in order to elucidate the mechanism and modular organization of cognitive control. Inspired by two influential theories regarding cognitive control, the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001) and dimensional overlap taxonomy (Kornblum, Hasbroucq, & Osman, 1990), we explored the temporal and spectral similarities and differences between processing of stimulus–stimulus (S–S) and stimulus–response (S–R) conflicts with event related potential (ERP) and time-frequency measures. We predicted that processing of S–S conflict starts earlier than that of S–R conflict and that the two types of conflict may involve different frequency bands. Participants were asked to perform two parallel SRC tasks, both combining the Stroop task (involving S–S conflict) and Simon task (involving S–R conflict). ERP results showed pronounced SRC effects (incongruent vs. congruent) on N2 and P3 components for both S–S and S–R conflicts. In both tasks, SRC effects of S–S conflict took place earlier than those of S–R conflict. Time-frequency analysis revealed that both types of SRC effects modulated theta and alpha bands, while S–R conflict effects additionally modulated power in the beta band. These results indicated that although S–S and S–R conflict processing shared considerable ERP and time-frequency properties, they differed in temporal and spectral dynamics. We suggest that the modular organization of cognitive control should take both commonality and distinction of S–S and S–R conflict processing into consideration.

Introduction

To perform a goal-directed action, we need to constantly exert cognitive (executive) control on information processing, which serves to maintain, update and manipulate task-relevant and irrelevant information via top-down modulation. In the laboratory, stimulus–response-compatibility (SRC) tasks, such as Stroop task (Stroop, 1935), Simon task (Simon and Rudell, 1967), and Flanker task (Eriksen and Eriksen, 1974), have been frequently used to study cognitive control, in which prepotent conflicting task-irrelevant information needs to be actively suppressed in order to correctly respond to the task-relevant stimulus (Botvinick et al., 2001; Ridderinkhof et al., 2004). The SRC effect refers to the finding that performance is inferior (i.e. slower and more erroneous response) in the incongruent condition as compared to the congruent condition. It is reasoned that SRC tasks usually involve mapping task relevant and irrelevant stimuli onto appropriate responses. In incongruent trials, participants may experience conflicts between task relevant and irrelevant stimuli or attributes (stimulus–stimulus, S–S), and/or conflicts between task irrelevant information and responses (stimulus–response, S–R). To overcome these conflicts, additional cognitive efforts may be allocated, which require top-down cognitive control.

The dimensional overlap (DO) theory provided a sound taxonomy of various SRC effects. According to this framework, SRC tasks can be classified on the basis of their dimensional overlap attributes, which are defined as the similarity in perceptual, structural, and conceptual properties, between multiple stimulus sets (i.e. S–S) or between stimulus and response sets (i.e. S–R) (Kornblum, 1994; Kornblum et al., 1990, 1999). By this definition, the Stroop task and Simon task belong to distinct DO types. In the manual Stroop task, the SRC effect results from the dimensional overlap between two stimulus attributes (i.e. color and word meaning), thus belongs to the S–S type of DO; whereas in the Simon task, the SRC effect is caused by the dimensional overlap between task irrelevant stimulus property (i.e. target location) and response (i.e. hand location), thus belongs to the S–R type of DO. Given this distinction, the DO theory predicts different processing patterns for different types of conflicts: the S–S conflict is resolved at an early stimulus–processing stage where information of task-relevant dimension is identified and passed to the following response-production stage; whereas the S–R conflict, if present, is processed at response-

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production stage through interaction between an automatic activation route and an intentional response-identification route (Kornblum, 1994). Regardless of specific processing routes, this two-stage model generally predicts that the SRC effect for the S–S conflict occurs earlier than that of the S–R conflict.

One way to investigate the difference in time courses of S–S and S–R conflict processing was to manipulate the stimulus onset asynchrony (SOA) of task relevant and irrelevant dimensions (De Jong et al., 1994; Hommel, 1997; Kornblum et al., 1999; Treccani et al., 2009). Another commonly used behavioral method was the distributional analysis, in which participants' RTs were grouped into bins according to values, then RTs of different bins were compared between compatible and incompatible conditions (De Jong et al., 1994; Hommel, 1997; Kornblum et al., 1999). However, both behavioral methods had methodological difficulties in revealing the time course of a homogenous process: the SOA method changed onset time of task elements therefore inevitably induced changes in mental processes; the distributional analysis could only reflect statistical properties of RT distributions (Zhang and Kornblum, 1997).

Electrophysiological correlate of cognitive process, with its high temporal resolution at the millisecond scale, is an excellent index to examine time course of S–S and S–R conflict processing. Several event-related potential (ERP) components of SRC effects have been identified. For example, Flanker N200, a larger negativity (incongruent minus congruent) in fronto-central regions around 200 ms after stimulus onset, was typically reported for flanker tasks (Heil et al., 2000; van Veen and Carter, 2002b). The Stroop effect was related to a component named N450, a fronto-centrally to centro-parietally distributed negativity (incongruent minus congruent) around 450 ms after stimulus onset (Liotti et al., 2000; Tillman and Wiens, 2011). Another typically reported ERP modulation of the SRC effect was P300 latency (later for incongruent than congruent trials) in Simon tasks (Donchin and Coles, 1988; Leuthold, 2011; Valle-Inclan, 1996).

In addition to ERP analysis of EEG data, time-frequency analysis can be used to reveal event-related oscillations (ERO) properties, which cannot be fully depicted by ERP (Makeig et al., 2004; Roach and Mathalon, 2008). Two typically used indices are event-related spectral perturbation (ERSP), mean change in spectral power (in dB) from baseline, and inter-trial coherence (ITC), strength (0 to 1) of phase locking of EEG signals to the events. Recent human EEG studies have linked the frontal midline theta (FM theta) rhythm to cognitive control. SRC effects in theta band were reported in the flanker task (Nigbur et al., 2011, 2012), Stroop task (Hanslmayr et al., 2008) and Simon task (Nigbur et al., 2011). Interestingly in the flanker studies, the ERSP of "stimulus conflict", in which target and flankers were mapped onto the same response, dissociated with the ERSP of "response conflict", in which target and flankers mapped onto the opposite responses. This dissociation suggested that ERSP might be a promising tool to explore possible distinction of time-frequency correlates of S–S and S–R conflict effects. Theta band is also closely related to other cognitive control mechanisms, including error detection (Cavanagh et al., 2009; Luu et al., 2004), task switching (Sauseng et al., 2006) and working memory (Sauseng et al., 2010).

To directly compare time courses of S–S and S–R conflict processing, an ERP study of SRC effects has to satisfy two conditions, which was not met by many of previous ERP studies. Firstly, given that ERP components are highly sensitive to physical properties of stimuli, these properties should be matched across S–S and S–R conflicts. Secondly, the same task should be performed to study both S–S and S–R conflicts to rule out task switching, which also requires top-down control, as a confound factor (Monsell, 2003). So far only one ERP study met the requirements above and showed that ERP correlates of S–S conflict occurred earlier than that of S–R conflict (Fruhholz et al., 2011). In their study, combining the flanker (S–S) task and Simon (S–R) task, a display consisted of a central target and four surrounding distractors presented laterally. However, it still contained two confounds. First, besides S–R conflict induced by the target location, spatial location of flankers also contributed to S–R conflict, causing an interaction of S–S and S–R conflicts. Secondly, each trial contained both types of DO (e.g., one trial can be both S–S incongruent and S–R incongruent). Since S–S and S–R conflict effects may interact with each other (Hommel, 1997; Kornblum et al., 1999; Treccani et al., 2009), this setup of stimuli could have caused problems in their results. For example, they failed to produce a significant Simon effect in behavioral measures in EEG and fMRI experiments, possibly due to overriding effect caused by the S–S conflict.

In the present study, we adopted two tasks from our previous behavioral and fMRI studies, both of which combined the Stroop and Simon tasks (Liu et al., 2004, 2010) and controlled for task switching, stimuli variability across conditions and interaction between S–S and S–R conflicts. EEG were recorded when participants were performing these two tasks. Based on the DO theory, we predicted that ERP correlates of S–S effect started earlier than those of S–R effect. Secondly, we predicted that S–S and S–R conflicts would differentially modulate frequency bands, reflecting recruitment of different neural mechanisms.

Methods

Participants

Twenty-six college students (13 women; 19–26 years old, M = 22.4, SD = 1.7) participated this study. All participants were right-handed, and all had normal or corrected-to-normal vision. No participant had a neurologic or psychiatric history. A signed informed consent form was obtained from each participant before the experiment. They were compensated for their participation.

Tasks and materials

All participants completed two tasks, Simon-color-Stroop (SCS) task and Simon-spatial-Stroop (SSS) task, in a counterbalanced order (see Fig. 1). Participants were seated 80 cm from the display (resolution, 1024 × 768 pixels, vertical refresh rate, 75 Hz) in a dimly lit room. Stimulus presentation and manual response measurement were controlled by E-Prime 2.0 (Psychological Software Tools, Inc., Pittsburgh, PA, USA). Participants were instructed to respond as quickly and accurately as possible.

Simon-color-Stroop task

The SCS task was adopted from a previous work (Liu et al., 2010) and modified for ERP experiment. All stimuli were presented on a gray background. Participants were trained to make a left or right key-press according to the color of the stimulus (red or blue) while ignoring other information. Training ended once the participant's accuracy reached 90%. Color-response mapping was counterbalanced across participants. During the test stage, a diamond (visual angle 4.9° × 4.9°) was presented in the center of the screen with half of the diamond (a triangle) painted in either red or blue (Fig. 1A). The triangle can point to one of the four directions (left, right, up, and down). A neutral (e. g., "杯" meaning cup), congruent (e. g., "蓝" meaning blue), or incongruent (e. g., "红" meaning red) Chinese character in black ink, was overlaid in the center of the diamond. In S–S conditions, the word was either "red" or "blue" and the triangle pointed up or down. In a congruent trial (SSC), the character matched the color of the triangle. In an incongruent trial (SSI), the character and the color did not match. In S–R conditions, the overlaying word was neutral (not related to colors) and the colored triangle pointed left or right. In a congruent trial (SRC), the pointing direction of the triangle matched the response location. In an incongruent trial (SRI), the triangle direction pointed to the opposite of the response location.

Participants performed one practice block of 20 trials and seven test blocks. Each test block consisted of 80 trials, with equal numbers of SSI, SSC, SRI and SRC trials intermixed randomly. Each trial lasted 2400 ms. A central fixation was presented for 100, 200 or 300 ms (randomly