Conflict monitoring and adjustment in the task-switching paradigm under different memory load conditions: an ERP/sLORETA analysis

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The aim of the present study was to examine electrophysiological and behavioral changes caused by different memory loads in a task-switching paradigm. A total of 31 healthy individuals were subjected to a task, in which the stimulus–response reversal paradigm was combined with the task-switching paradigm. The event-related potentials were recorded and the N2 component, an index of conflict processing, was measured. In addition, the neural sources of N2 were further analyzed by standardized low-resolution brain electromagnetic tomography. The event-related potential results showed that high memory load triggered a higher N2 mean amplitude. Moreover, the standardized low-resolution brain electromagnetic tomography data showed that high memory load caused an increase in current densities at the anterior cingulate cortex and the prefrontal cortex in the task-switching paradigm. In summary, our findings provide electrophysiological evidence to interpret possible influences of memory loads on conflict monitoring and modulation during the task switching. These results imply that the working memory load overrules the influence of task-switching performance on the intensification of cognitive control. *NeuroReport* 00:000–000 Copyright © 2015 Wolters Kluwer Health, Inc. All rights reserved.

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Introduction

In a high-stress society, individuals are inundated with multiple demands from work and household. It is essential for individuals to have the ability to flexibly and effectively tackle varied challenges; otherwise, there is failure to adjust to the diverse environments and maintain their health. Executive function (EF), including cognitive flexibility, working memory, and inhibition, plays a vital role in such adjustments [1]. Dysfunction and/or deficit in flexible control of individual behavior could lead to neuropsychiatric disorders, such as depression, obsessive-compulsive disorder, and attention deficit hyperactivity disorder [2–4]. Accordingly, it is imperative to identify the neurobiological mechanisms of the constituents of EF and the neuropathology of the relevant disorders. Previous studies dissociate the mechanisms of the components of EF by using more than one experimental paradigm [3,4]. However, there have been considerably fewer studies combining these elements of EF into a single task to investigate the neurophysiological substrates of EF, especially the basis of cognitive flexibility under different memory loads. Hence, the present study was designed to explore the neurophysiological characteristic when individuals flexibly modulate their performance under different working memory loads.

Cognitive flexibility is usually studied using the task-switching paradigms, in which the participants are required to shift among different tasks [1]. The premier switching-task paradigm is composed of mixed-task blocks (e.g. ABAB) and single-task blocks (e.g. AA or BB) [5–8]. Another classical alternating-runs paradigm, which consists of both switch trials and nonswitch trials (e.g. in AA**B**B**A**A**B**B, after the first run of AA**B**B trials, the trials of the next run were: **A**-switch; A-nonswitch; **B**-switch; B-nonswitch), is developed and widely studied [6–9]. As both these paradigms require the participants to hold the task sets (A and B) and the task orders in mind, working memory loads exist in both paradigms [6,8,9]. The AABB task sequence involves a higher memory load than the AA or BB or AB task sequence. However, the neural effects of the memory loads in both task-switching paradigms were still unknown.

To further understand the neural activity of a switching task, the event-related potential (ERP) approach, which allows detection of precise temporal information of neural activity, was used in previous studies. During diverse task-switching paradigms, multiple components have been found to relate to the switching process and among these, frontocentral and conflict-related N2 has been associated closely with inhibition [10–16]. For instance, N2 amplitudes on switching condition were increased during a response-switching or a task-set switching task [14–16]. These findings suggest that inhibition is an important source of the switch condition and the N2 component is a sensitive index. When switching between two different response rules or task sets, the previous task

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rule interferes with the current one and inhibition is required to resolve the interference [17,18]. The information processing of the switching task may fit in with the conflict monitoring hypothesis, which posits that the anterior cingulate cortex (ACC) detects the occurrence of conflicts and signals the information to recruit the cognitive control to enhance subsequent performance [19]. Although the electrophysiological correlates on task switching are well characterized, the neural mechanisms induced by different memory loads are rarely known.

Therefore, in the present study, we combined the stimulus–response reversal paradigm with the task-switching paradigm and examined the behavioral and neural differences in the task under different memory loads. We hypothesized that the task-switching experiment under high memory load would yield a greater N2 amplitude, whereas the one under low memory load would induce a lower N2 amplitude. Moreover, the cortical sources of the N2 component for these different conditions were compared by standardized low-resolution brain electromagnetic tomography (sLORETA).

Materials and methods

Participants

A total of 31 right-handed individuals (12 men, mean age 21.1 ± 1.2 years, range 18–24 years) from Dalian University of Technology in China participated in this study. All participants reported to have normal or corrected-to-normal vision.

Stimulus and procedure

A red circle (diameter 2.7 cm) on a black background was presented either at the left or at the right side within a centrally oriented white horizontal rectangle (3.9×14.7 cm). Two response patterns were provided on the basis of the stimulus–response reversal paradigm: compatible (which is stimulus–response-rule A) and incompatible (which is stimulus–response-rule B) [20]. For the compatible pattern, participants responded according to the correspondingly spatial location of the red circle (e.g. a left circle designated a left response button press). For the incompatible pattern, participants made a response according to the opposite location of the circle (e.g. a left circle designated a right response button press). The stimulus–response reversal paradigm, coupling with the switch task, involved four trial types: nonswitch with compatible response (NSCR), switch with compatible response (SCR), nonswitch with incompatible response (NSIR), and switch with incompatible response (SIR) (see the left panel of Fig. 1).

Meanwhile, to examine memory load effects, two conditions were compared using a within-participant experimental design (see the left panel of Fig. 1). Low memory load condition: an initial single-task block of 50 compatible-pattern trials, namely, NSCR (AA task sequence), was followed by another single-task block of 50 incompatible-pattern trials, namely, NSIR (BB task sequence). After two single-task blocks, 152 switch trials in the AB task sequence were presented. Task A was the SCR trial type and Task B was the SIR trial type. The participants were required to keep the A or B single task rule or AB switching rules in mind to make the correct response. High memory load condition: an alternating-runs (AABBAABB) paradigm with 324 trials was used. In this paradigm, the first A of AABB after a run performance was the SCR trial type, the second A of AABB was the NSCR trial type, the first B of AABB was the SIR trial type, and the second B of AABB was the NSIR trial type. The individuals were instructed to orderly maintain all the task sets of alternating-runs (AABB) in mind to make a correct response to the task.

After presentation of the task instructions, the stimulus of the red circle was displayed until the participants pressed a key. During the AB and AABB tasks, if participants made a wrong response, both the error message and a hint for correct response would be presented, and the stimulus would remain on the screen until the participants made a right reaction, which was still marked as incorrect. This was done to ensure that the participant smoothly continued the following performance, but was not affected by the wrong response. After the response, the white horizontal rectangle on the black background was still displayed for 2000 ms before the next trial appeared. All participants were instructed to respond as quickly and accurately as possible.

Behavioral data analysis

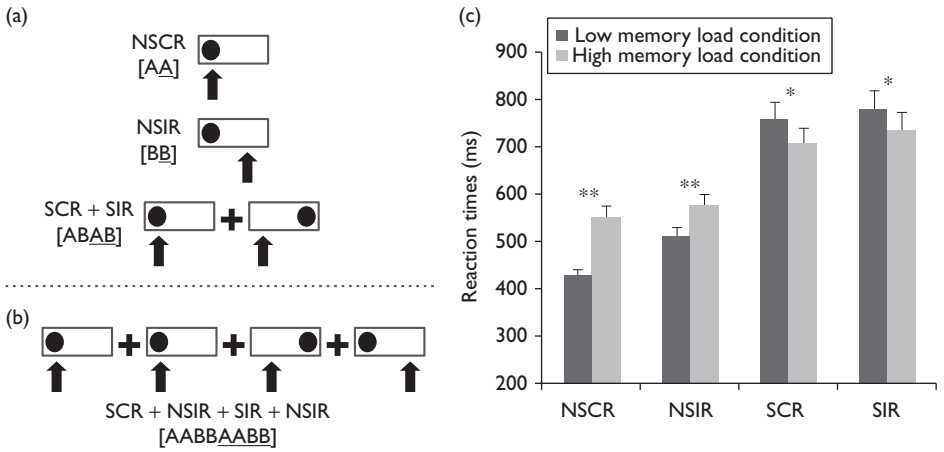
The first trial of each block was excluded because it was neither a switch trial nor a nonswitch trial. The error trials were excluded from the reaction time (RT) analyses. Response accuracy and mean RTs were, respectively, entered into a 4(trial type: NSCR, NSIR, SCR, SIR) $\times$ 2 (task condition: low and high memory load) repeated measures analysis of variance (Greenhouse–Geisser corrected).

Event-related potential recording and processing

The electroencephalogram was recorded from 64 Ag/AgCl scalp electrodes recording System (Brain Products GmbH, Munich, Germany); all these electrode sites followed the International 10–20 System nomenclature and the reference electrode was placed at the center between Fz and Cz. Both horizontal and vertical electrooculography were recorded with electrodes placed at the outer canthus of and above the left eye. All impedances were maintained below 10 kΩ. The hardware filter was between 0.0159 and 250 Hz and the signal sampling rate was 500 Hz.

Band pass and notch filtering (0.05–30 Hz; 50 Hz) were used offline. After the removal of eye movement artifacts, the electroencephalographic data were re-referenced to an average reference of all scalp electrodes. A trial was excluded from further ERP analysis if (a) its response time was less or more than three SDs of the mean RT for each trial type under different task conditions, (b) it was

Fig. 1



(a, b) Show examples of the correct response for each trial and trial type under low and high memory load conditions. Letters A and B represent two stimulus–response rules. A = compatible response; B = incompatible response. Letters with dashes indicate trial types shown on the boxes. Arrows indicate correct responses for trial types. Four trial types: NSCR, nonswitch with compatible response; NSIR, nonswitch with incompatible response; SCR, switch with compatible response; SIR, switch with incompatible response. The memory load conditions from up to down were: (a) low load condition, (b) high load condition, (c) mean and SE bar for reaction times obtained in NSCR, NSIR, SCR, and SIR trial types under low and high memory load conditions. $^{**}P < 0.001$; $^{*}P < 0.05$.

the first trial within each block, or (c) its responding button was wrongly pressed. Stimulus-locked data were segmented into epochs ranging from 100 ms before to 900 ms after the stimulus onset, and epochs were baseline corrected for the 100 ms preceding the stimulus. After rejecting epochs with the signal exceeding ±80 μV, the average ERPs were calculated separately for each trial type under different task conditions. Grand-averaged ERPs were obtained for participants.

Event-related potential data analysis

The previous review has shown that the N2 has a maximal amplitude at frontocentral scalp locations between 200 and 350 ms after stimulus [21]. On the basis of visual inspection of grand-average maps for each condition and previous review, the N2 mean amplitudes between 270 and 340 ms after stimulus onset were measured. The statistical analysis of N2 mean amplitudes included three electrodes (Fz, FCz, and Cz). For each participant, a 4(trial type: NSCR, NSIR, SCR, SIR) × 2(task condition: low and high memory load) × 3(electrode: Fz, FCz, Cz) repeated measures analysis of variance (Greenhouse–Geisser corrected) was performed on the N2 amplitude results.

Standardized low-resolution tomography analysis

We used sLORETA to locate the neural sources of significant differences at the N2 time window between experimental conditions [22]. In this study, the averaged ERP data within the N2 time frame (270–340 ms) were subjected to sLORETA and time-frame-wise normalized [23]. The paired *t*-tests on log-transformed data were carried out using sLORETA built-in randomization procedures (5000 permutations) to correct for multiple comparisons [24].

Results

Behavioral performance

For response data, the mean accuracy rates for NSCR and NSIR under both task conditions were above 99% whereas the rates for SCR and SIR under both task conditions were above 95%. Only the significant main effect of trial type was observed [$F(2, 48) = 11.62$, $P < 0.001$]. Post-hoc analysis showed that the accuracy of NSCR or NSIR was significantly higher than that of SCR or SIR trials (P's < 0.05), respectively.

For RTs, we found a significant interaction between trial type and task condition [$F(2, 59) = 29.96$, $P < 0.0001$]. Simple effect tests suggested that the RTs under the high memory load condition were significantly longer than the RTs under the low memory load condition within NSCR or NSIR trials (P's < 0.001). In contrast, the RTs under the high memory load condition were smaller than the RTs under the low memory load condition within SCR ($P = 0.039$) or SIR ($P = 0.040$) trials. The main effect of task condition was not significant, and yet the main effect of trial type was highly significant [$F(2,54) = 104.72$, $P < 0.0001$]. Post-hoc analysis indicated that the RTs of SIR trials (mean RT = 756.45 ms) were the greatest among the four trial types, and the RTs of SCR (mean = 733.29 ms) were greater than NSIR (mean = 543.80 ms) and NSCR (mean = 490.16 ms) (Bonferroni corrected post-hoc comparisons, all P's < 0.0001, except the pair of SCR and SIR with $P = 0.85$) (Fig. 1).

Event-related potential results

As shown in Fig. 2, the analysis for the N2 amplitude showed a significant main effect of trial type

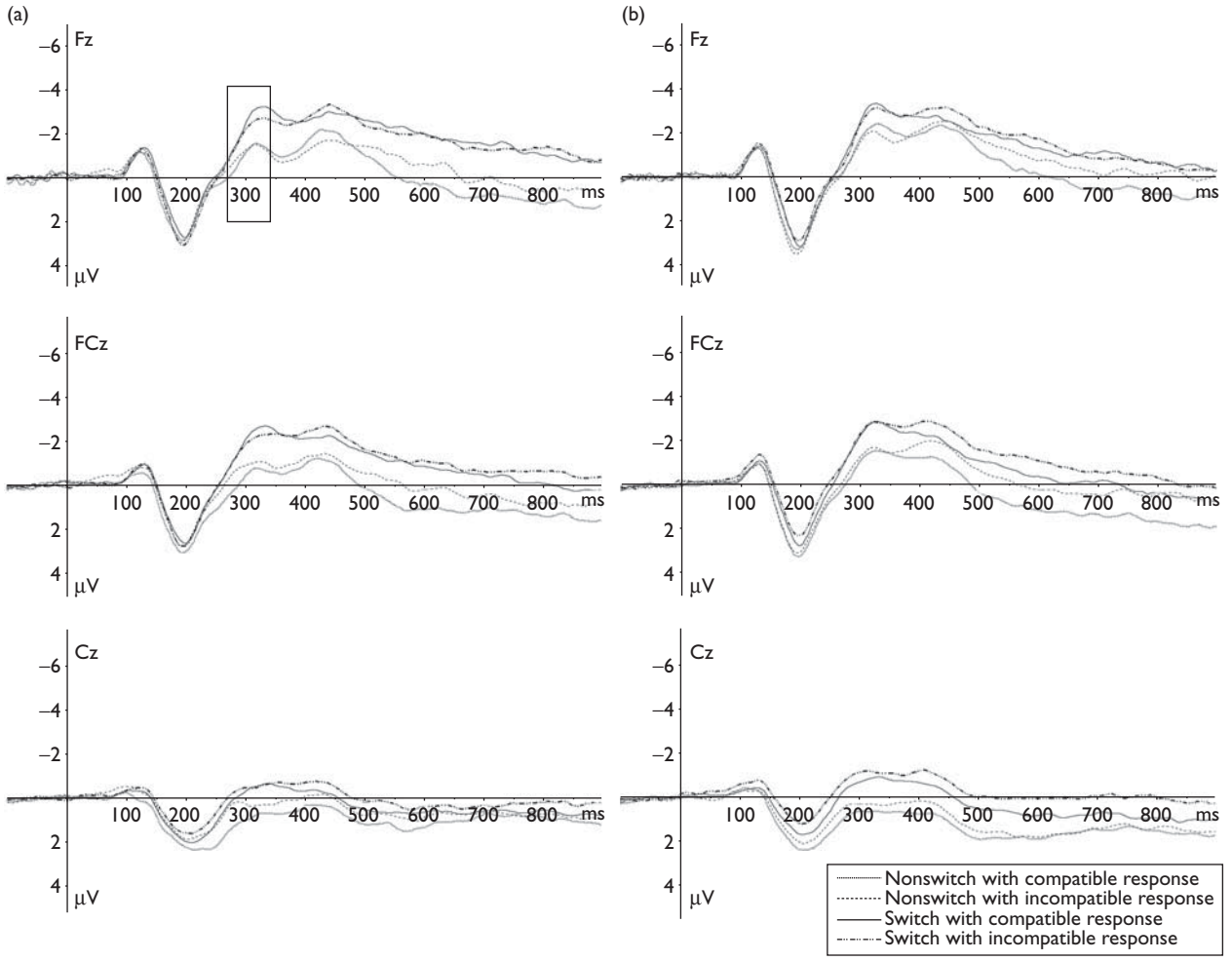
[$F(3, 75) = 19.06$, $P < 0.0001$]. Post-hoc analysis showed a significantly smaller (i.e. less negative) N2 amplitude for NSCR trials (−0.44 μV) compared with SCR trials (−1.67 μV) and SIR trials (−1.66 μV) (P's < 0.0001). NSIR trials also elicited a significantly smaller N2 mean amplitude (−0.69 μV) compared with SCR trials ($P < 0.005$) and SIR trials ($P < 0.0001$). This main effect was qualified by a significant interaction between trial type and electrode site [$F(4, 117) = 4.75$, $P < 0.01$]. Moreover, there existed a main effect of electrode site [$F(1, 38) = 25.33$, $P < 0.0001$], with pairwise comparisons indicating a significantly smaller amplitude at Cz (−0.08 μV) than Fz (−1.79 μV) and FCz (−1.47 μV) (P's < 0.0001). Finally, the statistical analysis also showed a main effect of task condition [$F(1, 30) = 8.61$, $P < 0.01$], indicating a much larger N2 amplitude under the high memory load condition (−1.32 μV) than that under the low memory load condition (−0.91 μV).

Standardized low-resolution brain electromagnetic tomography results

In the N2 mean amplitude analysis, the significant main effects for both trial type and task condition were found. Thus, the sLORETA-images were compared (a) between SCR and NSCR; (b) between SIR and NSIR; and (c) between high and low memory load conditions. All the significant differences for the cortical regions were set at less than 0.05 level.

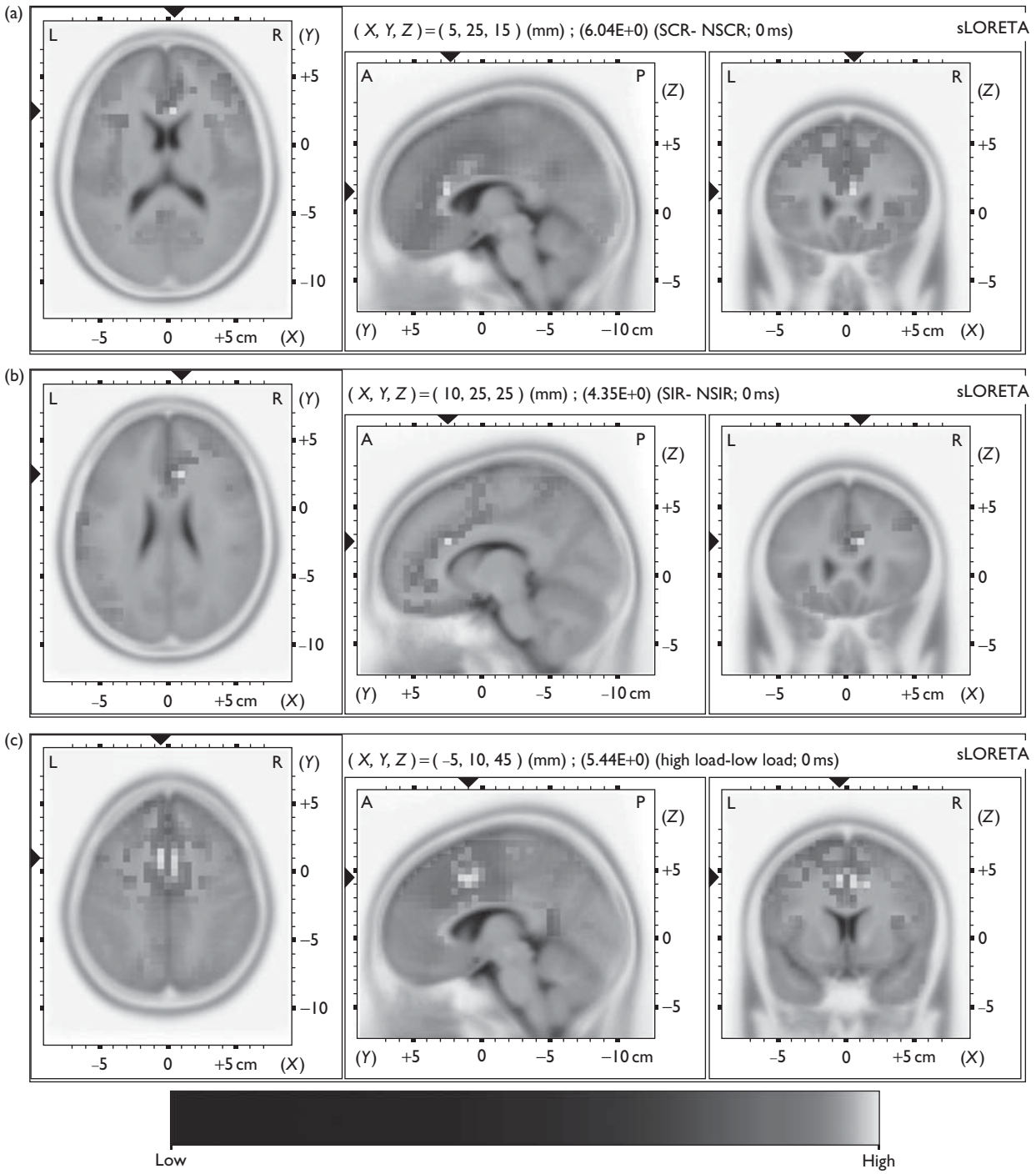
As shown in Fig. 3, the greatest difference between SCR and NSCR was found in the ACC located within the Brodmann area 24 (BA24). Meanwhile, compared with the NSCR condition, the current density in the SCR condition was significantly increased in the inferior frontal gyrus (BA11/47), superior frontal gyrus (BA10/11), medial frontal gyrus (BA9/10/11/32), middle frontal gyrus (BA11/47), orbital gyrus (BA11/47), and cingulate

Fig. 2



Grand-average stimulus-locked event-related potentials at Fz, FCz, and Cz under: (a) low memory load condition (b) high memory load condition. The box indicates the N2 time window (270–340 ms).

Fig. 3



sLORETA maps for the N2 component for the contrast: (a) between SCR and NSCR; (b) between SIR and NSIR; (c) between high and low memory load conditions. A, anterior; L, left; NSCR, nonswitch with compatible response; NSIR, nonswitch with incompatible response; P, posterior; R, right; SCR, switch with compatible response; SIR, switch with incompatible response; sLORETA, standardized low-resolution brain electromagnetic tomography.

gyrus (BA24/32). In contrast, on comparing the current density between SIR and NSIR, a significant change was only observed in ACC located in BA32.

In terms of the task condition, the comparison between high and low memory load conditions showed the highest current density in the cingulate cortex (BA32). In

addition, compared with the low memory load condition, the high memory load condition showed greater current density in the medial frontal gyrus (BA6/8/32), middle frontal gyrus (BA6/8), superior frontal gyrus (BA6/8), and cingulate gyrus (BA24/32).

Discussion

According to the behavioral performance, RTs of NSCR and NSIR under the low memory load condition were smaller than those under the high memory load condition, whereas the mean RT results of SCR and SIR under both low and high memory load conditions showed the reverse trends. These data indicated that working memory loads may contribute toward the response speed of trial type. More importantly, the current study found that the change trends of N2 amplitudes did not completely correspond with those of behavioral performance. Our ERP results showed that N2 amplitude under the high memory load condition was greater than that under the low memory load condition. The sLORETA results showed that the high memory load condition evoked larger current density in the frontal brain areas than the low memory load condition.

As indicated by previous review and studies [21,25,26], the frontocentral N2 component was associated with response inhibition, response conflict, and error monitoring, which are linked to cognitive control. This means greater N2 negativity related to a higher level of conflict monitoring and cognitive control. Compared with the low memory load condition (A or B or AB), the participants were required to maintain more task rules and task sequences in their working memory under a high memory load (AABB). Meanwhile, they need to repeatedly switch between alternative task rules. Thus, the greater N2-effect in the high memory load means that the participants need to allocate more executive resources to subserve the cognitive control. Furthermore, as we analyzed the N2-effect from the correct trials, the N2-effect in the task-switch experiment may reflect the time processes of successfully inhibiting the previous task-set and appropriately implementing the current task-set [18]. The electrophysiological activity in current research may show that a task-switching paradigm under a high working memory load is more sensitive for the conflict monitoring and adjustments than the one with a lower working memory load.

The process of different-memory-load-based task-switching performance, which reflected the conflict monitoring theory, was confirmed not only by the frontocentral N2 analysis but also by data from N2-related sLORETA. First, ACC was the maximum significant activated area (current density at the generator) for switch trial types compared with nonswitch trial types. The cingulate cortex was the brain region with the highest current density when comparing the high memory load condition with the low memory load condition. Previous research has indicated that the neural generator of the N2 component is considered to be localized to ACC, which is related to the response conflict monitoring [19,25–27]. Hence, our results suggest that high memory load enhances cognitive conflict and causes an increased activation of ACC to detect the conflict. Second, as mentioned in the classical conflict monitoring theory, the conflict signal that ACC detects gives rise to top-down control to adjust the manipulating strategy for the subsequent behavioral performance [19,27,28]. The prefrontal cortex (PFC) mainly contributes toward executing top-down control [28,29]. Our findings showed that the current density in PFC was higher for the high memory load condition than for the low memory load condition. Thus, the differential current density at PFC indicates the disparities in the behavioral adjustments and the assignment of control processes. All these findings suggest that the neural sources of N2 amplitudes reflect the processes of conflict detection and cognitive control in the current task-switching experiment with different memory loads. Finally, our data showed that the current density of BA9/10/11/24/32/47 was significantly higher during SCR relative to the NSCR condition, whereas BA32 was activated more during SIR than during NSIR. All these are consistent with the imaging findings on the switching task, which reflected crucial roles of the prefrontal areas in the switch function [30]. Another finding, that is, the current density of BA6/8/24/32 increased during high memory load compared with low memory load, is in line with the imaging study on working memory that the incremental activation in PFC was induced by the enhanced working memory load [31].

Taken together, our findings identified that the multiple prefrontal areas were intensified and coordinated to resolve the impending conflict action when the memory load that increased under switching-task performance lead to more conflict control. All of these results indicate that the working memory load overrules the influence of switching-task implementation on the intensification of cognitive control.

Conclusion

The present results showed that N2 and its current density at ACC and PFC were enhanced with the increased cognitive conflict for the high memory load condition in the task-switching paradigm. These findings are in agreement with the conflict monitoring theory, and provide a new perspective on cognitive control in task-switching studies.

It should be noted that functional MRI signal changes for task-switching paradigm were not acquired in the current study. Future studies will be needed to determine the

brain mechanisms of cognitive conflict for different memory loads in task switching using an ERP/functional MRI fusion approach.

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Conflicts of interest

There are no conflicts of interest.

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