Volume 87, No. 1, April 2011
87(1) 1–182
ISSN 0301-0511

BIOLOGICAL PSYCHOLOGY

Biological Psychology 87 (2011) 17–24

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

Pleasant mood intensifies brain processing of cognitive control: ERP correlates

Jiajin Yuan[a,b,*], Shuang Xu[a,b], Jiemin Yang[a,b], Qiang Liu[a,b], Antao Chen[a,b], Liping Zhu[a,b], Jie Chen[a,b], Hong Li[a,b,*]

[a] *Key Laboratory of Cognition and Personality (SWU), Ministry of Education, Chongqing 400715, China*
[b] *School of Psychology, Southwest University, Chongqing 400715, China*

ARTICLE INFO

Article history:
Received 15 June 2010
Accepted 9 January 2011
Available online 15 February 2011

Keywords:
Pleasant mood
Event-related potentials
Cognitive control
Stroop interference
N450

ABSTRACT

The present study investigated the impact of auditory-induced mood on brain processing of cognitive control using a Stroop color-word interference task. A total of 135 positive, negative, and neutral sounds (45 of each) were presented in separate blocks for a mood induction procedure, which was then followed by a Stroop color-word task in each trial. Event-related potentials (ERPs) were recorded for color-word congruent, incongruent and neutral (color-word irrelevant) words and subjects named the printed colors of the words by pressing the appropriate key (irrespective of word meaning). Response latency was delayed during incongruent vs. neutral trials, and this cost did not interact significantly with mood states. ERP data showed prolonged peak latencies in the P200 component and more negative deflections in the Late Positive Component (LPC, 450–550 ms) during incongruent vs. neutral conditions, regardless of mood states. Moreover, the negative deflections (N450) in the 450–550 ms interval of the incongruent- neutral difference waves, which index cognitive control effect in brain potentials, was more pronounced in the pleasant, but not in the unpleasant, mood state when compared with the neutral mood state. These data suggest that, pleasant mood intensifies brain processing of cognitive control, in a situation requiring effective inhibition of task-irrelevant distracting information. In addition, N450 component serves as an affective marker, embodying not only cognitive control effect in the brain but also its interaction with mood states.

1. Introduction

Many situations in everyday life require inhibitory control of task-irrelevant distracting information to accomplish goal-directed behavior and to keep thought and action in accordance with intention. This process is cognitive control that, as indicated (Cohen et al., 2000), is an important brain function that makes us human. There was plentiful evidence that the implantation of cognitive control is influenced substantially by mood states (Botvinick et al., 2001; Rowe et al., 2007; Yuan et al., 2008). For example, high school students are well able to control outside distracters during class time, but this control becomes hard usually in the last lesson of a week, when students are preoccupied by the excitement of going home for the weekend. In addition to this anecdotal evidence, numerous empirical studies have revealed a modulating effect of mood state on the processes of cognitive control (Gray, 2001; Phillips et al., 2002; Rowe et al., 2007). In an early study, Gray investigated the impact of mood on the information maintenance component of cognitive control during a two-back working memory task that used video excerpts as mood-induction material. Results showed a facilitation effect of positive mood and an impairing effect of negative mood on verbal working memory performance. Interestingly, this pattern was reversed on a spatial working memory task (Gray, 2001). In addition, Phillips and colleagues used an emotion–memory procedure to investigate the effects of happy mood on cognitive control by measuring response time on a Stroop color-word task (Phillips et al., 2002). Results showed that, compared to the neutral mood condition, the happy mood condition produced greater Stroop and task-alternating costs, which served as indices of the effects of cognitive control.

Distinct from early evidence that positive mood facilitates some aspects of cognitive control, such as working memory and cognitive flexibility (Ashby et al., 1999; Gray, 2001), recent studies consistently revealed that positive mood induction, which is associated with increased brain dopamine (DA) levels in frontal cortical areas (Cohen et al., 2002; Schultz, 2002), impairs cognitive control by decreasing the task maintenance and increasing the attention to irrelevant, novel information (Dreisbach and Goschke, 2004; Mitchell and Phillips, 2007). In particular, the results provided

---

* Corresponding authors at: School of Psychology, Southwest University, No. 1 of Tiansheng Road, Beibei, Chongqing 400715, China. Tel.: +86 23 68253629; fax: +86 23 6825 2309.
E-mail addresses: yuanjiajin168@126.com, yuanjiaj@swu.edu (J. Yuan), lihong1@swu.edu.cn (H. Li).

0301-0511/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.biopsycho.2011.01.004

by Mitchell and Phillips (2007) in a recent review of the influence of mood state on executive function indicate that negative mood has little effect on cognitive control, a higher cognitive process that requires focused attention. In contrast, positive mood, which is associated with heuristic thinking and divided attention (Mitchell and Phillips, 2007), impairs cognitive control processes such as planning and task switching most likely as a result of impaired focused attention (Rowe et al., 2007). Consistent with this view, a study by Rowe and colleagues revealed no significant influence of negative mood on cognitive control during an Eriksen flanker task, while they found an impairing effect of positive mood (Rowe et al., 2007). In addition, a recent ERP study using an AX-CPT (Continuous Performance Task) paradigm showed decreased brain potentials associated with conflict monitoring during pleasant mood induction (Van Wouwe et al., 2011). All these evidence showed an impairing, instead of promoting, effect of pleasant mood on brain processing of cognitive control. Nevertheless, the ERP study by Dennis and Chen (2007) found no significant impact of emotional faces on the performance of a peripheral flanker task. More recently, Hart and colleagues used functional MRI to demonstrate enhanced response time delay for color-word incongruent words primed by aversive emotional pictures. Moreover, this study provided support for the role of a set of cognitive control-related neural structures, such as dorsolateral prefrontal cortex, inferior frontal gyrus, and cingulated cortex, involved in this effect (Hart et al., 2009).

Based on the previous research, it is clear that there remains some debate regarding the impact of mood on cognitive control processes. This is likely due to the fact that cognitive control includes multiple components (e.g., multiple forms of working memory, task maintenance, task switching and self-monitoring; Gray, 2001; Phillips et al., 2002), and different studies employed distinct methods for mood induction and the quality of mood maintenance varied (Rowe et al., 2007; Hart et al., 2009). Despite its multiple forms, the essential component of cognitive control is consistently recognized as the inhibition of task-irrelevant thought and information during the performance of the central task (Cohen et al., 2000; Botvinick et al., 2001; Chen et al., 2008). In addition, effective mood induction and maintenance are vital prerequisites for the study of the effects of mood on cognitive control. Static emotional scenes are useful for inducing short-lived emotional responses rather than stable mood states (Yuan et al., 2007; Dennis and Chen, 2007), while the emotion–memory procedure and focused mood induction (followed by many trials), are effective for mood induction but not for maintenance (Phillips et al., 2002). Consequently, both are unsuitable, to some extent, for an investigation of the effects of mood on cognitive control. Moreover, most of the previous studies used behavioral measures as indices of the impacts of mood on cognitive control (e.g., response time). Without neurophysiological measures, behavioral measures alone are insufficient for identifying what happens in the brain during the performance of cognitive control tasks with mood induction. To date, few studies have used neurophysiological measures to unravel the temporal dynamics of the modulating effects of cognitive control by mood induction. Though there was recent evidence showing smaller N2 amplitudes for mismatching probes in pleasant mood during an AX-CPT task (Van Wouwe et al., 2011), the lack of a negative mood condition makes it hard to attribute the results exclusively to positive mood, instead of general mood arousal; while probe-induced ERPs in this task may also index outcome evaluation (e.g. whether a prior response to the "A" cue is correct) other than response conflict monitoring. Thus, it is necessary to run another ERP study using a different paradigm, with full consideration of the above factors, for the purpose of clarifying the impact of mood states on cognitive control and its spatiotemporal dynamics in the brain with effective mood induction and maintenance.

Based on these considerations, the present study used ERP measures and a block design mood-priming procedure to investigate the impact of mood on cognitive control processes. Affective sound excerpts, each lasting between 4 and 5 s, were used for stable mood induction and were followed by a Stroop color-word task. We utilized a block design in which only one category of affective sounds was presented in a block. The purpose of this method was to improve the quality of mood induction and maintain the homogeneity of the mood state in each block. To control for possible mood attenuation, we preceded each Stroop test trial with an affective sound presentation, rather than following focused mood induction with many trials. In addition, the Stroop color-word task was used instead of other cognitive control tasks because the key processing involved in this task is simple and appropriate for the central feature of cognitive control (i.e., the inhibition of task-irrelevant stimulus information). Consequently, task performance was less likely to be affected by other cognitive faculties, such as attention span (Rowe et al., 2007) or working memory (Gray, 2001).

Moreover, it is known that brain processing of cognitive control involves multiple stages, such as early perceptual processing and attention elicitation that provide a basis for the subsequent inhibitory control, and the late stage of conflict detection and resolution (Qiu et al., 2006; Chen et al., 2008; Yuan et al., 2008). The former process was evidenced to be associated with an early frontal P2 activity (Chen et al., 2008; Qiu et al., 2006), while the latter process was indicated to be indexed by a Late Positive Component (LPC) in brain potentials (Markela-Lerenc et al., 2004; Peng et al., 2004; Liotti et al., 2000). Particularly, the LPC ranges from about 350–600 ms and was reported more negative during the cognitive control compared to non-control conditions. This effect was often manifested by a pronounced N450 component in the difference waves whose amplitude behaves as a direct index of the size of cognitive control effect (Qiu et al., 2006; Chen et al., 2008; Liotti et al., 2000). Based on these evidence, the LPC amplitude differences between cognitive control and non-control conditions would vary across mood states if mood has a significant impact on cognitive control in the present study. This impact would then be manifested by different amplitudes across mood states in N450 component of the difference waves which, as stated above, directly indexes the size of cognitive control effect. Therefore, the present study analyzes early P2, and late LPC components, especially focusing on the mood and stimulus type interaction on the LPC amplitudes that indicates an influence of mood on cognitive control processing. Because several behavioral studies have shown that positive affect, which worsens focused attention and enhances divided attention (Mitchell and Phillips, 2007), impairs cognitive control performance during Stroop tasks (Phillips et al., 2002; Rowe et al., 2007), we hypothesized that subjects may commit more errors in labeling ink colors during color-word incongruent trials along with smaller N450 activity for correct performance trials in the pleasant block. Alternatively, given that fast and accurate performance of color naming is overtly required in the experiment, the subjects' behavioral performance is also likely non-impaired with the engagement of more mental efforts for inhibiting task-irrelevant semantic information in the pleasant mood. In this case, subjects would achieve similar task performance in the presence of intensified cognitive control in the brain, which would be reflected by larger N450 amplitudes, i.e. larger differences between cognitive control and non-control conditions in LPC amplitudes, in the pleasant compared to other mood states.

2. Materials and methods

2.1. Subjects

Participants were 14 paid, college student volunteers (7 males, 7 females) enrolled at Southwest University in China. They were between the ages of 19 and

26 years (mean age: 21.8). All subjects were right-handed, and free of color blindness. Further, each subject had normal or corrected-to-normal vision, reported no history of affective disorders and was not taking any psychiatric medications. The study was approved by the local review board for human participant research, and each subject gave informed consent prior to participating in the experiment.

2.2. Stimuli and experimental procedure

The present study used the Stroop interference task. A block design method was adopted for mood induction. Depending on the mood state, the experiment was divided into three blocks: pleasant, neutral and unpleasant. Therefore, the audio stimuli used in each block shared the same valence and induced a single kind of mood. This is a double-blind procedure about the block sequence. The order of blocks was randomized across subjects. Each block contained 135 trials, including 45 incongruent trials consisting of four color words (red, yellow, green, blue, written in Chinese), each written in a color not matching the word meaning (e.g., the word "green" written in red ink); 45 congruent trials consisting of the four words written in the color matching the word meaning (e.g., the word "red" written in red ink); and 45 neutral trials consisting of three color- irrelevant words (ball, watch, pen, written in Chinese) written in each of the four colors.

The onset sequence of the three types of stimuli was randomized for each subject. Prior to the presentation of each word, an affective sound excerpt was delivered to a set of earplugs through air tubes to prevent electromagnetic artifacts from becoming part of the affective context. The 135 pleasant, neutral and unpleasant sounds were selected from the native Chinese Affective Digitized Sound system (CADS; Liu et al., 2006). Based on the dimension theory of emotion (Lang, 2002), CADS was developed in the Key Laboratory of Mental Health at the Chinese Academy of Sciences, using the method normalized by NIMH (Bradley and Lang, 1999). The purpose of its development was to facilitate the study of auditory-induced affect in Chinese-speaking population. To develop CADS, researchers collected 850 sound excerpts and ultimately kept 453 that possessed both fine sound quality and clear meanings for normative rating. The pretest for this system showed that CADS is reliable for emotional induction (Liu et al., 2006). A one-way ANOVA of valence showed higher valence scores for pleasant sounds (6.81) than for neutral sounds (4.86); in turn, the valence scores for the neutral sounds were higher than those of the negative sounds (3.33; $F(2, 132) = 614.9$; $p < 0.001$). On the other hand, a one-way ANOVA of arousal showed a similar pattern of medium arousal for pleasant (5.43), neutral (5.23) and unpleasant sounds (5.64, $F(2, 132) = 2.86$; $p > 0.05$). The size of the Chinese characters was Song Ti No. 28 1.4° (horizontal) × 1.4° (vertical), and was displayed at random at the center of a 17-in. screen.

2.3. Behavioral procedures

Subjects were seated approximately 80 cm from a computer screen in an acoustically isolated room. Prior to the experiment, subjects were told that they would be participating in a color-naming task; they were instructed to rest their left middle, left index, right index and right middle fingers on the s, d, j and k keys, each of which represented one color. Each trial was initiated by the presentation of a small, black cross in the center of a silver display screen; this concurred with the 4 or 5 s presentation of an affective sound excerpt. Between 300 and 500 ms after the offset of the fixation cross and the sound excerpt, a stimulus word written in one of four colors was presented. Subjects were asked to identify the color in which the word was written as quickly and accurately as possible by pressing the button corresponding to the proper color. Word presentation was terminated by a key press or after 1500 ms, whichever occurred first. Therefore, responses had to be given within this time limit. Each response was followed by a 1000 ms presentation of a blank screen. A practice session consisting of 10 trials was used to allow subjects to build the mapping of response fingers and colors. The practice session repeated until subjects were familiar enough with the response map to achieve 90% accuracy. Subjects who reached 90% accuracy during practice then proceeded to participate in the experiment. Throughout the block, subjects were instructed to keep their eyes fixated on the monitor rather than looking down at their fingers. At the end of each block, subjects assessed their affective state by completing the Positive Affect and Negative Affect Schedule (PANAS, Watson et al., 1998). They were then given the opportunity to take a break. The next block was initiated after subjects reported that their mood had returned to a quiet, affectively neutral state (Fig. 1).

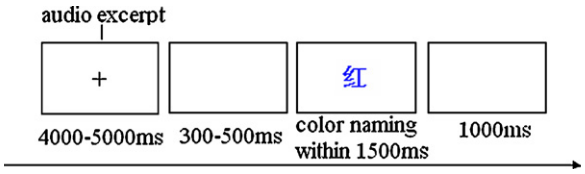

Fig. 1. Schematic illustration of the behavioral procedure in a trial.

2.4. ERP recording and analysis

EEG was recorded from 64 scalp sites using tin electrodes mounted on an elastic cap (brain products). Reference electrodes were located on the left and right mastoids (average mastoid reference, Luck, 2005), and a ground electrode was placed on the medial frontal aspect. Vertical electrooculograms (EOGs) were recorded supra- and infra-orbitally at the left eye. The horizontal EOG was recorded from the left vs. right orbital rim. The EEG and EOG were amplified using a DC∼100 Hz bandpass and were continuously sampled at 500 Hz/channel. All inter-electrode impedance was maintained below 5 kΩ. Averaging of ERPs was computed off-line. Eye movement artifacts (blinks and eye movements) were rejected offline and a 16 Hz low-pass filter was used. Trials with EOG artifacts (mean EOG voltage exceeding ±80 μV) and those contaminated with artifacts due to amplifier clipping or peak-to-peak deflection exceeding ±80 μV were excluded from averaging. The percentage of trials rejected for each condition was low enough (<7%) for a sufficient number to be used for ERP averaging.

The EEGs for correct responses during either word condition (incongruent vs. neutral) were averaged for each block. The number of trials with correct responses were no less than forty for each of the six mood and stimulus type conditions. There were 41.59 trials for unpleasant, 41.71 trials for neutral and 42.07 trials for pleasant blocks during color-word incongruent condition; while there were 41.30 trials for unpleasant, 41.45 trials for neutral and 41.55 trials for pleasant blocks during the color-word neutral block. ERP waveforms were time-locked to the onset of word stimuli, and the averaged epoch for ERPs was 1000 ms (including a 200 ms pre-stimulus baseline). The following electrode sites were selected for statistical analysis: F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz and P4. We did not include color-word congruent trials for analysis to avoid the facilitation effect often found in cognitive control studies (Schroeter et al., 2004, 2007; MacLeod, 1991). Inspection of the averaged ERPs showed a pronounced P2 in the 150–250 ms time interval, and an LPC (late positive component) in the 450–550 ms time interval during both word conditions, irrespective of mood (Fig. 3). Moreover, there was an obvious effect of color-word interference in the LPC (450–550 ms) time interval, although the strength of these effects varied across mood conditions (Fig. 4). Therefore, we measured the peak latencies and amplitudes of P2 (150–250 ms), and the averaged amplitudes of LPC (450–550 ms) in each individual subject. Then, repeated measures analysis of variance (ANOVA) were conducted on the peak amplitudes and latencies of P2, and on the average amplitudes of the LPC component using the following factors as repeated factors: mood (three levels: pleasant, neutral and unpleasant), stimulus type (two levels: incongruent and neutral), frontality (five levels: frontal, frontocentral, central, centroparietal, parietal) and laterality (three levels: left, midline, right) as repeated factors. Instead of peak amplitudes, average amplitudes were measured for the LPC time window because there were no obvious peaks in the 450–550 ms interval during the incongruent condition. The degrees of freedom for the F-ratio were corrected according to the Greenhouse–Geisser method.

3. Results

3.1. Behavioral performance

Incorrect responses were rare, as each subject achieved more than 90% accuracy in the color-word incongruent and neutral conditions of each block. In addition, response accuracy was similar in the unpleasant (92.1%), neutral (92.4%) and pleasant (93.0%, $F(2, 26) = 1.24$; $p = 0.31$) blocks, irrespective of stimulus type. The ANOVA of response time (RT) data did not reveal a significant mood by stimulus type interaction ($F(2, 26) = 0.15$; $p = 0.86$). The size of the incongruent-neutral difference was 58.9 ms for the unpleasant mood state, 59.2 ms for the pleasant mood state, and 64.2 ms for the neutral mood state. However, there was a significant effect of stimulus type ($F(1, 13) = 49.53$; $p < 0.001$), as incongruent words (728 ms) elicited longer RTs than neutral words (667 ms). In addition, color-naming responses were faster during pleasant (679 ms) than unpleasant (712 ms; $p < 0.01$) or neutral (700 ms; $p < 0.1$) blocks, which is evident by a trend of mood effect ($F(2, 26) = 2.99$; $p < 0.07$). Therefore, despite enhanced overall performance in the pleasant mood condition, mood state had no significant influence on cognitive control at the behavioral level.

3.2. Mood induction assessed by PANAS

A repeated-measures ANOVA of scores on the positive scale showed a significant effect of mood ($F(2, 26) = 7.94$, $p < 0.01$). Post

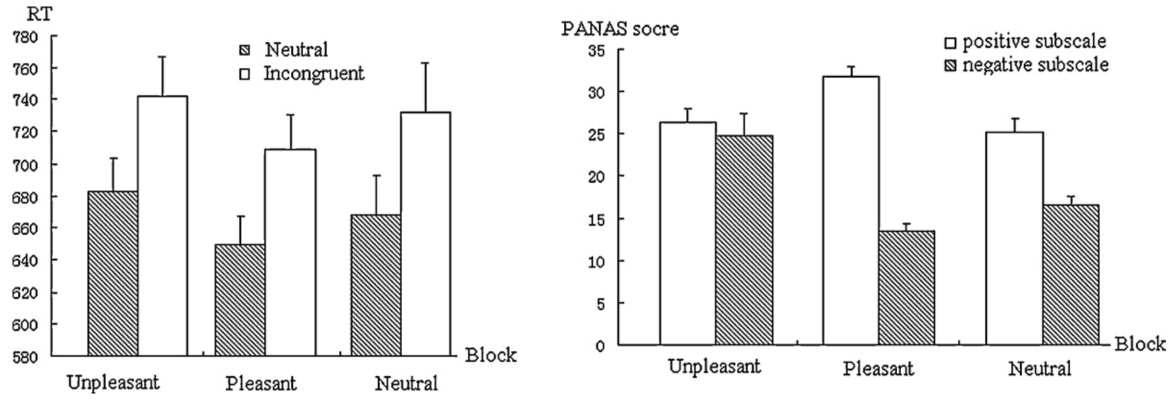

Fig. 2. Left: Schematic illustration of response times (RT) for neutral and incongruent conditions during unpleasant, pleasant and neutral blocks. Right: schematic illustration of the results of PANAS measurement during each block.

hoc analyses revealed higher scores during pleasant (31.90) than during neutral (26.28, $p < 0.01$) or unpleasant (25.12, $p < 0.01$) blocks. Moreover, the ANOVA of scores on the negative scale showed a significant effect of mood ($F(2, 26) = 19.99$, $p < 0.001$). Post hoc analyses revealed higher scores during unpleasant (24.79) than during neutral blocks (16.43, $p < 0.01$). Scores in the neutral block, in turn, were higher than those in the pleasant block (13.57, $p < 0.05$). Therefore, each block was effective at inducing the corresponding mood state (Fig. 2).

3.3. ERP results

A repeated measures ANOVA of P2 amplitudes showed neither main effects of mood ($F(2, 26) = 0.98$, ns) and stimulus $F(1, 13) = 0.32$, ns), nor their interaction ($F(2, 26) = 1.86$, ns), whereas the main effect of frontality was significant ($F(4, 52) = 18.08$, $p < 0.01$). Central and frontal sites recorded larger amplitudes than did posterior sites. The analysis of P2 latencies demonstrated significant main effects of frontality ($F(4, 52) = 5.46$, $p < 0.05$) and laterality ($F(2, 26) = 5.85$, $p < 0.05$), as well as a laterality and stimulus interaction ($F(2, 26) = 4.88$, $p < 0.05$). P2 peaked earlier at central and frontal sites (mean: 198.5 ms) than at parietal scalp sites (mean: 205.1 ms), whereas peak latencies were prolonged at right sites in comparison to left and midline sites. The breakdown of the laterality and stimulus interaction showed prolonged peak latencies for incongruent words in comparison to neutral words at right-lateralized sites (205.4 ms vs. 208.9 ms, $p < 0.05$), but not at the midline (198.6 ms vs. 200.1 ms) or left (201.8 ms vs. 202.9 ms) sites. However, the main effects of mood ($F(2, 26) = 0.22$, ns), stimulus $F(1, 13) = 0.80$, ns); and their interaction ($F(2, 26) = 0.85$, ns) all failed statistical significance (Fig. 3).

The ANOVA of the LPC amplitudes revealed significantly less pronounced amplitudes for incongruent than for neutral words, which is evident from the significant main effect of stimulus type ($F(1, 13) = 27.55$, $p < 0.001$). Moreover, there were significant interaction effects between frontality and laterality ($F(8, 104) = 10.79$, $p < 0.001$), and between laterality and stimulus type ($F(2, 26) = 7.20$, $p < 0.01$). The amplitudes in this interval were largest at the midline parietal scalp sites, whereas the color-word interference effect (measured by the incongruent-neutral ERP differences) was more pronounced at left than at right sites (Fig. 4). Furthermore, there was a significant interaction between stimulus type, mood and frontality ($F(8, 104) = 2.95$, $p = 0.005$). To deconstruct this three-way interaction, we broke down the factor of frontality and analyzed the stimulus type and mood interaction at each frontality level. This analysis did not reveal a significant interaction between mood and stimulus type at the frontal ($F(2, 26) = 0.37$, ns) or centrofrontal ($F(2, 26) = 0.05$, ns) sites. The size of the color-word interference effect was similar across mood conditions at these sites (1.28 μV for the unpleasant, 1.35 μV for the neutral and 1.54 μV for the pleasant mood states).

However, there was a significant stimulus and mood interaction at the central ($F(2, 26) = 3.98$, $p < 0.05$) and centroparietal ($F(2, 26) = 6.67$, $p < 0.05$) scalp sites, as well as a trend of stimulus and mood interaction at the parietal scalp sites ($F(2, 26) = 2.96$, $p < 0.07$). To further breakdown the stimulus and mood interaction, we tested the simple effect of stimulus in the pleasant, unpleasant and neutral blocks respectively at central-to-parietal scalp sites. The results showed a significant stimulus effect during both pleasant ($F(1, 13) = 16.87$; $p = 0.001$; $M_{\text{incongruent-neutral}} = 6.93 - 9.07 = -2.14$); neutral ($F(1, 13) = 8.83$; $p < 0.05$; $M_{\text{incongruent-neutral}} = 6.60 - 8.01 = -1.41$) and unpleasant ($F(1, 13) = 9.28$; $p < 0.01$; $M_{\text{incongruent-neutral}} = 6.61 - 7.99 = -1.38$) mood states. However, the size of the color-word interference effect, namely, the size of amplitude differences between incongruent and neutral conditions, was significantly larger during the pleasant mood than during the neutral ($F(1, 13) = 7.25$; $p < 0.05$) mood. Neutral mood condition, in contrast, displayed similar size of interference effect as the negative mood condition ($F(1, 13) < 1$, ns). To better present these results, we computed incongruent-neutral difference ERPs that directly index cognitive control effect in brain potentials (see Fig. 4). The difference ERPs in the 450–550 ms interval, as embodied by a clear N450 component, showed more pronounced amplitudes during pleasant than during the other two mood conditions ($F(2, 26) = 5.23$; $p < 0.05$). Therefore, we observed an impact of mood induction on cognitive control in the LPC time interval (450–550 ms), with enhanced brain processing of cognitive control in the pleasant mood state. This was manifested by enlarged N450 amplitudes in the incongruent-neutral difference ERPs in the pleasant mood state (see Fig. 4).

To verify whether the stimulus effect measured in the LPC interval was indeed associated with cognitive control of incompatible word meanings, we conducted a correlation analysis between the N450 amplitudes and the incongruent-neutral RT cost in the neutral mood block, where the stroop effect was free of mood influences. The results showed a significant negative correlation between N450 amplitudes and RT costs, with the RT costs increasing with more negative amplitudes ($r = -0.64$, $p < 0.02$). In addition, the same pattern of correlation was also observed in the pleasant mood state ($r = -0.51$; $p < 0.04$), during which the cognitive control effect in brain potentials was enhanced. Therefore, in the present study, the N450 amplitudes, which resulted from the ERP differences between incongruent and neutral conditions in the 450–550 ms interval,

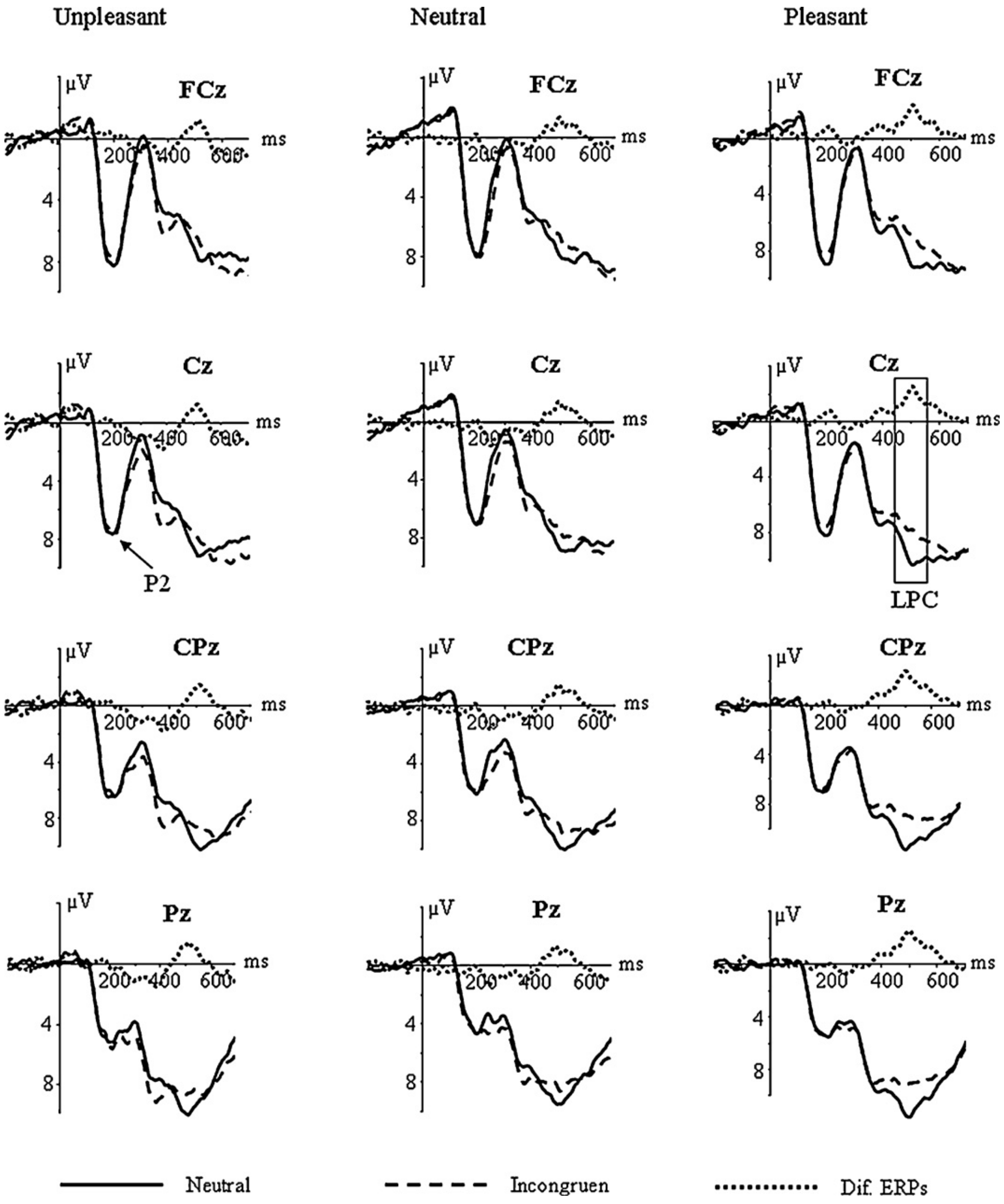

Fig. 3. Averaged ERPs for neutral (solid lines) and incongruent (dashed lines) words and their difference ERPs (dotted lines) during pleasant, neutral and unpleasant mood blocks.

were valid ERP markers of the cognitive control effect and its interaction with mood state.

3.4. Control analysis: whether sex moderates the impact of mood?

In order to examine whether sex moderates the effect of cognitive control and its association with mood, we conducted a control analysis of LPC amplitudes, which embodied the effect of cognitive control in brain potentials, by adding sex as a covariate. The results showed no significant effect of gender on LPC amplitudes ($F(1, 12) = 0.42$; $p = 0.53$). In addition, sex did not significantly interact with mood ($F(2, 24) = 3.07$; $p > 0.5$) and stimulus type ($F(1, 12) = 0.27$; $p = 0.61$). Moreover, the reliability of the mood, stimulus type and frontality interaction was not significantly influenced by sex, either; indicated by the non-significant four-way interaction among sex, mood, stimulus and frontaltiy ($F(8, 96) = 0.82$, $p = 0.51$). Therefore, sex did not significantly influence brain processing of cognitive control and its interaction with mood states in the present study.

4. Discussion

In line with numerous studies examining the Stroop effect (Stroop, 1935; Tsao et al., 1981; Sumiya and Healy, 2004; Atkinson et al., 2003), the present study revealed a significant Stroop interference effect at the behavioral response level, with incongruent words eliciting prolonged response latencies in comparison with neutral words. This finding suggests that the present paradigm, which added mood-inducing sound excerpts to the Stroop task, is effective at generating the classic Stroop interference effect. Thus, the present paradigm is valid for studying the impact of mood state on the processing of cognitive control. In addition, behavioral responses were generally faster in the pleasant mood condition when compared to the neutral and unpleasant mood

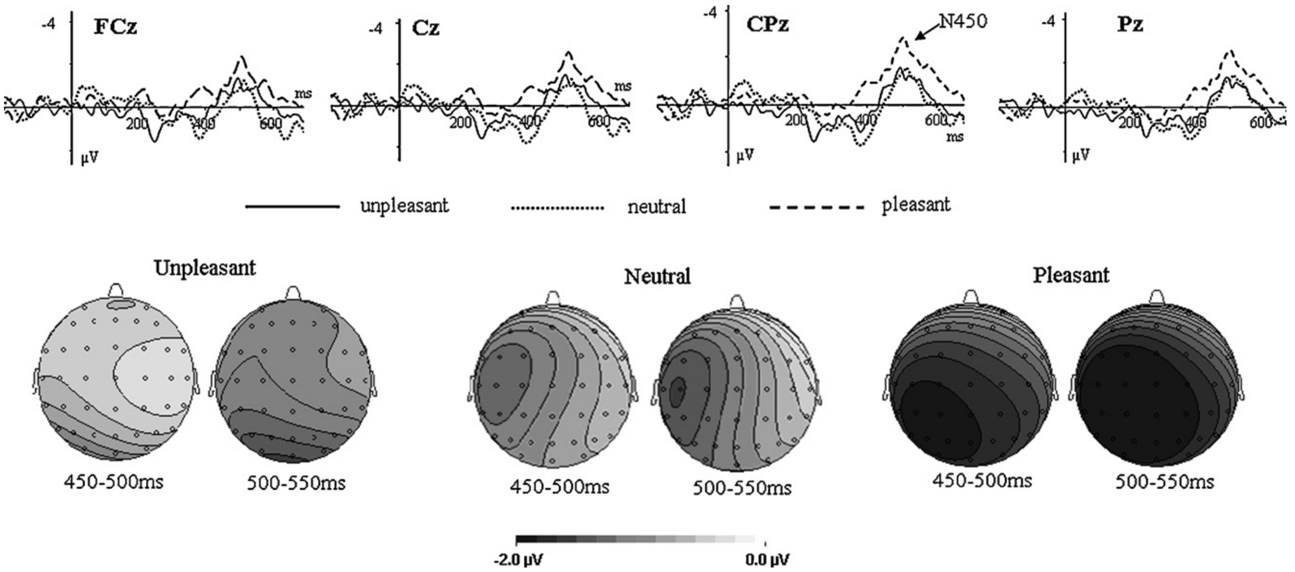

Fig. 4. Top pane incongruent-neutral difference ERPs for unpleasent (solid lines), neutral (dotted lines) and (dashed lines) mood states. Bottom panel: topographical maps for the difference ERPS in the 450–55 ms interval during unpleasent mood states.

conditions. This held true regardless of color-word congruence, possibly because a pleasant mood promotes simple, cognitive control-irrelevant processes like color perception (Van Loon et al., 2010). Moreover, ERP data revealed significant Stroop interference effects at the P2 and LPC components, as well as a significant impact of mood state on the processing of cognitive control in the LPC interval (450–550 ms). The implications of these findings are discussed in the following sections.

The P2 component observed in this study was more pronounced and had shorter peak latencies at the frontal and central scalp sites than at the parietal scalp sites, regardless of mood state (see Fig. 3). Therefore, the scalp distribution of P2 in this study fits the classic frontal P200 that is associated with perceptual analysis and attention allocation (Bigman and Pratt, 2004; Chen et al., 2007; Yuan et al., 2009). The magnitude of frontal P2 activity was considered an index of the intensity of perceptual processing (which requires attention allocation to function), and the peak latency was taken as an indication of the time required for perceptual analysis (Chen et al., 2007; Donchin, 1981). P2 amplitudes in the present study were prominent, but did not differ between the incongruent and neutral conditions and among the three types of mood conditions (see Fig. 3). This is likely due to the fact that P2 occurs at an early time point (at approximately 200 ms), when information processing occurs automatically and higher cognitive resources are inaccessible (Sergent et al., 2005). This finding is in line with prior studies revealing significant cognitive control-related Stroop interference effects only at late P3 or LPC (late positive component) components in both adults and adolescents (Qiu et al., 2006; Peng et al., 2004; Markela-Lerenc et al., 2004; Liotti et al., 2000). Thus, the cognitive control effect and its interaction with mood may occur at later processing stages in the present task. In addition, peak latencies of P2 were delayed for right vs. left lateralized sites, as well as in incongruent vs. neutral conditions for right instead of left sites. This implies that the left hemisphere, as indicated by prior studies (Franklin et al., 2008; Tokar et al., 1989), is more efficient in color processing. Consequently, the lexical attributes of the words least affected color perception when the left hemisphere (as opposed to the right hemisphere) was involved in perceptual processing (Li et al., 2003).

Central to the present study, we revealed a significant effect of cognitive control and a significant modulating effect of mood state on cognitive control processing in the 450–550 ms interval. This was in agreement with the results by Markela-Lerenc et al. (2004), which showed that semantic processing of word meanings, as well as the interference of semantic meaning on color identification is reflected in later ERPs in the 450–550 ms time interval. In the present study, although subjects intentionally attempted to attend to the color dimension of the words while ignoring the semantic meaning during the color-word incongruent condition, the processing of color information was inevitably interrupted by the incongruent semantic meaning being processed automatically (Li et al., 2003). Consequently, color and meaning bring about conflict and, accordingly, the activation of cognitive control-relevant neural substrates (e.g., the anterior cingulated cortex or the prefrontal cortex; Markela-Lerenc et al., 2004) is required to inhibit task-irrelevant semantic information for subjects to respond correctly. On the other hand, word meaning is irrelevant to the printed color in the neutral condition; thus, the prioritized processing of word meaning does not interfere (or interferes the least) with the central task of color-naming. Therefore, incongruent-neutral differences in behavioral or neurophysiological measures are indices of the cognitive control effect in the present task. Consistent with our hypothesis, we observed more negative deflections during incongruent than during neutral conditions in the LPC interval (450–550 ms), which was manifested by an N450 component in the incongruent-neutral difference waves that directly index the effect of cognitive control (Qiu et al., 2006; Peng et al., 2004; Markela-Lerenc et al., 2004; Liotti et al., 2000).

More importantly, we observed a significant effect of stimulus type; a significant interaction between stimulus type and laterality; and a three-way interaction among stimulus type, frontality and mood on the LPC amplitudes of the 450–550 ms time interval. Incongruent words elicited more negative deflections than did neutral words, irrespective of mood state. This finding suggests that the present mood-priming Stroop task, in line with the classic Stroop task, is effective at eliciting the color-word interference effect and cognitive control processing (Markela-Lerenc et al., 2004; Liotti et al., 2000; Carter et al., 1995). This interference effect was more pronounced at the left scalp areas, which is consistent with prior reports that the left cortical areas (e.g., the left prefrontal and temporal–parietal regions) are more involved in word-meaning processing and its cognitive suppression (Markela-Lerenc et al., 2004; Liotti et al., 2000). More importantly, the cognitive control effect, indexed by the size of incongruent-neutral amplitude differences in the 450–550 ms interval, was significantly more pronounced during the pleasant mood condition compared to the neutral and unpleasant mood conditions. This effect was manifested by a more prominent N450 component in the incongruent-neutral difference waves during pleasant mood induction (Figs. 3 and 4). As indicated by the breakdown of the three-way interaction, the impact of mood on cognitive control processing was most pronounced at the central-to-parietal scalp sites, instead of a classic frontocentral scalp distribution (Qiu et al., 2006; Markela-Lerenc et al., 2004). This finding is likely the result of using affective sound excerpts for mood induction, which may involve affective memories and experiences mediated by parietal and temporal lobes (Koelsch and Siebel, 2005).

The present study revealed that the Stroop interference effect on behavioral measures, such as RT delay for incongruent trials, was unaffected by mood induction. This finding is possibly due to the inclusion of training trials and the stringent criterion for performance (90% accuracy) in the practice session, consequently resulting in subjects becoming familiar and skillful enough with the task and the response pattern. Although the behavioral measures were unaffected, the neurological effect of Stroop interference, which was manifested by increased negativity during incongruent vs. neutral conditions in the 450–550 ms interval, was more pronounced with pleasant than with neutral or unpleasant mood induction. This suggests that on one hand, N450 component of brain potentials is a more sensitive measure than the response time index, in revealing cognitive control effect and its interaction with mood states. The N450 as an ERP marker of cognitive control effect is valid, as shown by prior studies (Liotti et al., 2000), and by the significant correlation between N450 amplitudes and RT costs observed in the present study. On the other hand, pleasant mood has been indicated to result in reduced maintenance and increased distractibility, consequently leading to enhanced attention to novel, task-irrelevant interfering information (Dreisbach and Goschke, 2004). Therefore, pleasant mood probably distracts subjects from the central task of color-naming to a greater extent compared to unpleasant mood. Accordingly, the task-irrelevant word meanings were likely to access more attention in the pleasant mood, which must have brought in greater conflicts and thus required more intense cognitive control, in order to accomplish the task of labeling the word color and responding by fast and accurate key presses, irrespective of the semantic meaning of the words.

Therefore, cognitive control of the prepotent processing of task-irrelevant word meanings had to be enhanced in pleasant mood than in unpleasant and neutral mood states, to maintain a comparably good level of behavioral performance in the present study. As a result, the N450 amplitude, which behaved as an ERP marker of the cognitive control effect, was enhanced during pleasant mood induction. This result was exclusively attributed to the impact of pleasant mood, instead of the effect of general mood arousal, because this effect was absent in the unpleasant block whose arousal was matched with that of the pleasant block. Previous studies suggested that pleasant mood is associated with increased divided attention, heuristic processing and cognitive flexibility, thereby worsening individuals' performance on tasks requiring focused attention (Dreisbach and Goschke, 2004; Mitchell and Phillips, 2007). Accordingly, empirical evidence indicates that pleasant mood results in increased interference costs in RTs, and decreased brain activity of conflict monitoring during classic cognitive control tasks such as the Stroop, the Erikson flanker, and the AX-CPT tasks (Phillips et al., 2002; Van Wouwe et al., 2011), whereas unpleasant mood rarely influences this process (Rowe et al., 2007; Mitchell and Phillips, 2007). Based on these findings, pleasant mood, but not unpleasant mood, was suggested to impair processes of cognitive control (Rowe et al., 2007; Phillips et al., 2002). Consistent with this account, we observed that pleasant mood intensifies brain processing of cognitive control, such that more controlling resources were recruited in the pleasant mood to successfully inhibit task-irrelevant word meanings that otherwise involve nearly automatic processing (Wang and Yuan, 2008; Li et al., 2003); while unpleasant mood, which is relevant to focused attention, has no significant impact on cognitive control (Rowe et al., 2007; Phillips et al., 2002). The present study, however, develops our understanding of this phenomenon by showing that the impairing effect of pleasant mood may also be embodied by non-impaired behavioral performance as a result of intensified cognitive control in the brain, in addition to the prevalent results of impaired behavioral performance in the pleasant mood (Rowe et al., 2007; Phillips et al., 2002). Moreover, we showed that N450 amplitude is a valid index, which not only marks cognitive control effect in the brain but also embodies how this effect interacts with stable mood states.

5. Conclusions

Using affective sound excerpts and a classic Stroop color-word task, the present study observed that reliable mood state has a significant impact on the brain's processing of cognitive control. This effect was manifested by the intensified brain processing of cognitive control in the pleasant, but not in the unpleasant, mood states. N450 amplitudes, which were measured by the incongruent-neutral amplitude differences, served as markers of the cognitive control effect in the brain and its interaction with mood states.

Acknowledgments

This study was supported by National Natural Science Foundation of China (NSFC30 970897), National Key Discipline of Basic Psychology at Southwest University (NSKD08 015) and the Doctoral Foundation of Southwest University (SWU109028). The authors thank Dr. Joseph Dien and the two anonymous reviewers for their helpful comments, and thank Dr. Qiu J. for any discussion during this work.

References

Ashby, F.G., Isen, A.M., Turken, U., 1999. A neuropsychological theory of positive affect and its influence on cognition. Psychological Review 106, 529–550.

Atkinson, C.M., Drysdale, K.A., Fulham, W.R., 2003. Event-related potentials to Stroop and reverse Stroop stimuli. International Journal of Psychophysiology 47, 1–21.

Bigman, Z., Pratt, H., 2004. Time course and nature of stimulus evaluation in category induction as revealed by visual event-related potentials. Biological Psychology 66, 99–27.

Botvinick, M., Braver, T., Barch, D., Barch, M., Cohen, J., 2001. Conflict monitoring and cognitive control. Psychological Review 108, 624–652.

Bradley, M. M., Lang, P. J., 1999. International Affective Digitized Sounds (IADS): Stimuli, Instruction Manual and Affective Ratings (Tech. Rep. No. B-2). The Center for Research in Psychophysiology, University of Florida, Gainesville, FL.

Carter, C.S., Mintun, M., Cohen, J.D., 1995. Interference and facilitation effects during selective attention: an $H_2{}^{15}O$ PET study of Stroop task performance. NeuroImage 2, 264–272.

Chen, A., Yao, D., Wang, Q., Yuan, J., Luo, Y., Li, H., 2007. Electrophysiological correlates of category induction: PSW amplitude as an index of identifying shared attributes. Biological Psychology 76, 230–238.

Chen, A., Xu, P., Wang, Q., Luo, Y., Yuan, J., Li, H., et al., 2008. The timing of cognitive control in partially incongruent categorization. Human Brain Mapping 29, 1028–1039.

Cohen, J.D., Botvinick, M., Carter, C.S., 2000. Anterior cingulate and prefrontal cortex: Who's in control? Nature Neuroscience 3, 421–423.

Cohen, J.D., Braver, T.S., Brown, J.W., 2002. Computational perspectives on dopamine function in prefrontal cortex. Current Opinion in Neurobiology 12, 223–229.

Donchin, E., 1981. Surprise!. Surprise? Psychophysiology 18, 493–513.

Dennis, T.A., Chen, C.-C., 2007. Neurophysiological mechanisms in the emotional modulation of attention: The interplay between threat sensitivity and attentional control. Biological Psychology, 761–810.

Dreisbach, G., Goschke, T., 2004. How positive affect modulates cognitive control: reduced perseveration at the cost of increased distractibility. Journal of Experimental Psychology: Learning Memory, and Cognition 30, 343–353.

Franklin, A., Drivonikou, G.V., Bevis, L., Davies, R.L., Kay, P., Regier, T., 2008. Categorical perception of color is lateralized to the right hemisphere in infants, but to the left hemisphere in adults. Proceedings of the National Academy of Sciences of the United States of America 105, 3221–3225.

Hart, S.J., Green, S.R., Casp, M., Belger, A., 2009. Emotional priming effects during Stroop task performance. NeuroImage 47, 39–41.

Koelsch, S., Siebel, W.A., 2005. Towards a neural basis of music perception. Trends in Cognitive Sciences 9, 578–584.

Lang, P.J., 2002. The dimensional organization of emotion. In: Smith, E.E., Nolen-Hoeksema, S., Fredrickson, B.L., Loftus, G. (Eds.), Atkinson and Hilgard's Introduction to Psychology. , 14th ed. Wadsworth Thompson Learning.

Li, R.B., Peng, D.L., Guo, T.M., 2003. A study on Chinese and English semantic access with ERP technology. Acta Psychologica Sinica 36, 309–316.

Liotti, M., Woldorff, M.G., Perez, R., Mayberg, H.S., 2000. An ERP study of the temporal course of the Stroop color-word interference effect. Neuropsychologia 38, 701–711.

Liu, T.S., Ma, H., Huang, Y.X., Luo, Y.J., Yan, J., Liu, W.Z., 2006. Primary study of establishing an affective sound system of China. Chinese Mental Health Journal 20, 709–712.

Luck, S.J., 2005. An Introduction to Event-Related Potentials and their Neural Origins. MIT, Cambridge, MA, p 107.

MacLeod, C.M., 1991. Half a century of research on the Stroop effect: an integrative review. Psychological Bulletin 109, 163–203.

Markela-Lerenc, J., Ille, N., Kaiser, S., Fiedler, P., Mundt, C., Weisbrod, M., 2004. Prefrontal-cingulate activation during executive control: which comes first? Cognitive Brain Research 18, 278–287.

Mitchell, R.L.C., Phillips, L.H., 2007. The psychological, neurochemical and functional neuroanatomical mediators of the effects of positive and negative mood on executive functions. Neuropsychologia 45, 617–629.

Peng, D.L., Guo, T.M., Wei, J.H., Xiao, L.H., 2004. An ERP study on processing stages of children's Stroop effect. Science Technology and Engineering 4, 84–88.

Phillips, L.H., Bull, R., Adams, E., Fraser, L., 2002. Positive mood and executive function: Evidence from Stroop and fluency tasks. Emotion 2, 21–22.

Qiu, J., Luo, Y.J., Wang, Q.H., Zhang, F.H., Zhang, Q.L., 2006. Brain mechanism of Stroop interference effect in Chinese characters. Brain Research 1072, 186–193.

Rowe, G., Hirsh, J.B., Anderson, A.K., 2007. Positive affect increases the breadth of attentional selection. In: Proceedings of the National Academy of Sciences of the United States of America , 104, pp. 383–388.

Schroeter, M.L., Zysset, S., Wahl, M.M., von Cramon, D.Y., 2004. Prefrontal activation due to Stroop interference increases during development—an event-related fNIRS study. NeuroImage 23, 1317–1325.

Schroeter, M.L., Cutini, S., Wahl, M.M., Scheid, R., Cramon, D.Y., 2007. Neurovascular coupling is impaired in cerebral microangiopathy—an event-related Stroop study. NeuroImage 34, 26–34.

Schultz, W., 2002. Getting formal with dopamine and reward. Neuron 36, 241–263.

Sergent, C., Baillet, S., Dehaene, S., 2005. Timing of the brain events underlying access to consciousness during the attentional blink. Nature Neuroscience 8, 1391–1400.

Stroop, J.R., 1935. Studies of interference in serial verbal reactions. Journal of Experimental Psychology 18, 643–662.

Sumiya, H., Healy, A., 2004. Phonology in the bilingual Stroop effect. Memory and Cognition 32, 752–758.

Tokar, D.M., Matheson, N.K., Haude, R.H., 1989. Lateralization differences for color-naming and color-matching in men and women. Perceptual Motor Skills 69, 651–656.

Tsao, Y.C., Wu, M.F., Feustal, T., 1981. Stroop interference: hemispheric difference in Chinese speakers. Brain and Language 13, 372–378.

Van Loon, A.M., van den Wildenberg, W.P.M., van Stegeren, A.H., Hajcak, G., Ridderinkhof, K.R, 2010. Emotional stimuli modulate readiness for action: a transcranial magnetic stimulation study. Cognitive, Affective and Behavioral Neuroscience 10, 174–181.

Van Wouwe, N.C., Band, G.P.H., Ridderinkhof, K.R., 2011. Positive affect modulates flexibility and evaluative control. Journal of Cognitive Neuroscience 23 (3), 524–539.

Wang, Q.H., Yuan, J.J., 2008. N400 lexicality effect in highly blurred chinese words: evidence for automatic processing. NeuroReport 19, 173–178.

Watson, D., Clark, L.A., Tellegen, A., 1998. Development and validation of brief measures of positive and negative affect: the PANAS scales. Journal of Personality and Social Psychology 54, 1063–1070.

Yuan, J.J., Zhang, Q.L., Chen, A.T., Li, H., Wang, Q., Zhuang, Z.C.X., Jia, S.W., 2007. Are we sensitive to valence differences in emotionally negative stimuli? electrophysiological evidence from an ERP study. Neuropsychologia 45, 2764–2771.

Yuan, J.J., Yang, J.M., Meng, X.X., Yu, F.Q., Li, H., 2008. The valence strength of negative stimuli modulates visual novelty processing: Electrophysiological evidence from an ERP study. Neuroscience 157, 524–531.

Yuan, J.J., He, Y.Y., Lei, Y., Yang, J.M., Li, H., 2009. Event-related potential correlates of the extraverts' sensitivity to valence changes in positive stimuli. NeuroReport 12, 1071–1076.