Journal of Biomedical Optics

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Abstract. Conflict processing is crucial for humans and has been investigated using hemodynamic and electrophysiological measures. However, because most previous research has studied hemodynamic and electrophysiological measures separately, the relationship between these two measures in conflict processing is poorly understood. In our study, we measure near-infrared spectroscopy (NIRS) and event-related potential (ERP) signals simultaneously in a Chinese color-word matching Stroop task and examine the relationship between the conflict-related hemodynamic signal in the prefrontal cortex (PFC) and electrophysiological signal. The results show significant Stroop effects for behavioral, NIRS (oxy-hemoglobin: HbO_2), and ERP [N450, late positive complex (LPC)] data. The significant N450 Stroop effect occurs before the behavioral response to incongruent stimuli, while the evident LPC Stroop effect occurs after it, suggesting that only N450 is associated with conflict processing. Additionally, N450 Stroop effects during the early and later phases are negatively correlated with HbO_2 Stroop effects in the left PFC and in the bilateral PFC, respectively. These results suggest that N450 reflects conflict detection and resolution, the left PFC may be involved in conflict detection, and the bilateral PFC is engaged in conflict resolution. Overall, the analysis of the correlation between hemodynamic and electrophysiological signals is useful for studying human brain function. *© The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JBO.18.9.096014]

Keywords: near-infrared spectroscopy; event-related potential; Stroop task; prefrontal cortex; N450; late positive complex.

Paper 130069R received Feb. 14, 2013; revised manuscript received Jul. 2, 2013; accepted for publication Aug. 26, 2013; published online Sep. 25, 2013.

1 Introduction

Cognitive control is a key characteristic of the human cognitive system. It refers to the ability to attend to goal-relevant information, ignore distracting information, overcome conflict, and select the appropriate response. Cognitive control over conflict usually relies on conflict detection and resolution, and it has been widely studied using the Stroop task. In the classic Stroop task,[1] subjects are instructed to identify the color in which a word stimulus is printed. Usually, behavioral responses to incongruent stimuli (when the word and the ink color are incongruent, e.g., the word "blue" shown in green ink) are slower and less accurate than responses to neutral or congruent stimuli (when the word and the ink color are the same). The behavioral difference between incongruent and neutral or congruent stimuli is called the Stroop effect, which has been used as an index of cognitive control. Because the Stroop task is also useful for studying neurological/psychiatric disorders,[2,3] investigating its neural correlates can both improve our understanding of conflict processing and provide knowledge for practical uses.

A number of functional neuroimaging studies have investigated the neural correlates of the Stroop task and have identified that the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC) are involved in Stroop conflict tasks.[4–7] The PFC has been proven to play a predominant role in cognitive control.[8,9] The PFC implements top-down attention control to bias the neural processing of task-related information and resolve conflict.[9–11] Regarding conflict detection, the conflict monitoring theory asserts that the ACC detects the occurrence of conflict and then sends conflict-related information to the PFC, which resolves the conflict.[6,12] However, some studies have questioned the ACC's role in conflict detection,[9,13] and an increasing amount of research has suggested that the PFC also plays a role in conflict detection.[9,14,15]

Regarding electrophysiological measures, the previous event-related potential (ERP) studies have revealed two primary ERP markers in the Stroop task: N450 and the late positive complex (LPC).[16–20] N450 is more negative in amplitude for incongruent stimuli than for neutral or congruent stimuli. It has been generally considered to be related to conflict detection and resolution,[16,21] although some studies have suggested that N450 only reflected conflict detection.[22,23] The LPC amplitude is

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more positive for incongruent stimuli than for neutral or congruent stimuli. The cognitive processes reflected by the LPC are even more ambiguous than those reflected by N450. Some studies have suggested that the LPC was related to the additional processing of word meaning,[16,17] while others have proposed that this component was linked to conflict resolution.[22,23] Some studies have also suggested that the LPC reflected the conflict adaptation process.[24,25]

Although the previous neuroimaging studies have provided insight into the neural correlates of the Stroop task, most research has studied the hemodynamic and electrophysiological signals separately and the relationship between these two types of signals is still poorly understood.[7,26] Considering that an analysis of the relationship between hemodynamic and electrophysiological signals could inprove our understanding of human brain function,[26,27] it is necessary to study the relationship between these two types of signals to better understand the neural correlates of conflict processing.

Near-infrared spectroscopy (NIRS), a noninvasive optical functional neuroimaging method, can measure the concentration changes of oxy-hemoglobin ($\Delta[HbO_2]$) and deoxy-hemoglobin ($\Delta[Hb]$) to reflect relative regional brain activity. Previous studies using NIRS have successfully investigated the neural correlates of the Stroop task[28,29] and have improved our understanding of the PFC's role in conflict processing.[5,30] In addition, NIRS can be conveniently integrated with simultaneous electroencephalography (EEG) recordings.[26,31] Thus, it is appropriate to investigate the relationship between conflict-related hemodynamic and electrophysiological signals by combining NIRS and EEG. Our previous study has combined NIRS and ERP to investigate the relationship between hemodynamic and electrophysiological signals in a Stroop task and obtained some significant results.[26] However, the NIRS data were collected from only four detector channels with our portable brain function imager,[32] and the ERP data were recorded from only four frontopolar electrodes, which might overlook the presence of the N450 Stroop effect. Such limited measurement of the NIRS and ERP signals restricted the analysis of the relationship between hemodynamic and electrophysiological signals in conflict processing.

In this study, we aimed to examine the relationship between the conflict-related hemodynamic signal and the electrophysiological signal by combining NIRS and ERP. Since a color-word matching Stroop task primarily activates the lateral PFC,[5,13] it is more suitable for NIRS due to its low penetration depth.[31] We employed a Chinese color-word matching Stroop task and measured the hemodynamic signal from the PFC and the electrophysiological signal simultaneously during the task. Compared with our previous study, the NIRS signal was recorded from a larger prefrontal region using our newly developed brain function imager,[33] which emits and detects light with optical fibers. The ERP signal was recorded from anterior to posterior cortical sites.

2 Methods

2.1 *Subjects*

Fifteen students (seven women) aged 20 to 27 years [mean, 23.36 years; standard deviation (SD), 2.09 years] participated in this study as paid volunteers. All the participants were right handed and had normal or corrected-to-normal vision and normal color vision. All the subjects were healthy and had no personal or family history of neurological or psychiatric disorders. The volunteers received a complete description of the experiment and gave their written informed consent before the experiment. This study was approved by the Human Subjects Institutional Review Board at Huazhong University of Science and Technology.

2.2 *Materials*

The color-word matching Stroop task was used with a block design adapted from the previous studies.[13] Each stimulus consists of two Chinese characters, and the subjects were instructed to judge whether the color of the upper character corresponded to the meaning of the lower character [Fig. 1(a)]. If the answer was "match," the subjects pressed a button with the index finger of their left hand; if the answer was "unmatch," they pressed another button with the index finger of their right hand. There were two stimulus conditions: neutral and incongruent [Fig. 1(a)]. For neutral stimuli, the upper characters were non-color words (涂, 贯, 华, 球, 奖 meaning "scrawl," "pass through," "China," "ball," and "prize") presented in red, yellow, blue, green, or purple, and the lower characters were color words (红, 黄, 蓝, 绿, 紫 meaning "red," "yellow," "blue," "green," and "purple") printed in white. For incongruent stimuli, the upper characters were color words shown in a disparate color. The subjects were instructed to attend to the upper character first and then make their decision. This instruction was used to prevent subjects from ignoring the upper character. For each stimulus condition, the color of the upper character was the same as the meaning of the lower character in half of the trials, whereas the color of the upper character differed from the meaning of the lower character in the other half of the trials. Moreover, the "same" and "different" trials were semi-randomly mixed within each block to avoid the consecutive appearance of more than three "same" or "different" trials.

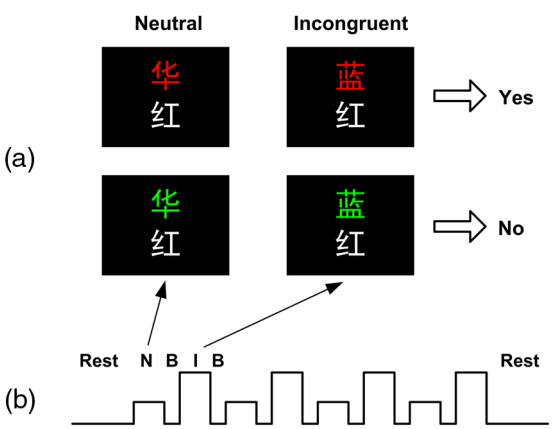

Fig. 1 Experimental design. (a) Trial examples for the neutral and incongruent conditions. The subjects were instructed to judge whether the color of the upper character corresponded to the meaning of the lower character. The correct answer was "match" for the upper two trial examples and "unmatch" for the lower two trial examples. 华 means "China" and 蓝, 红 corresponds to "blue, red." (b) The task sequence in each run. Rest, 1-min rest period before and after each run; B, 15-s baseline between blocks within each run; N, 30-s neutral task block; I, 30-s incongruent task block.

2.3 *Procedures*

The experiment consisted of four runs with four alternating block pairs of neutral and incongruent conditions (i.e., eight blocks) in each run [Fig. 1(b)]. Each block contained 20 trials, and within each trial, the stimulus was shown for 1200 ms, followed by a 300-ms blank screen. Subjects were instructed to respond to the stimuli as quickly and accurately as possible right after the stimuli presentation. A white cross appeared for 15 s between blocks within each run and for 60 s before and after each run, indicating a rest period. One second before each block, a sound alerted the subjects that the task was beginning. Subjects were told to avoid any major body movement during the experiment. Before the formal experiment, there was a practice session to familiarize the subjects with the task instructions.

2.4 *NIRS Recording*

The NIRS data were acquired using a continuous-wave NIRS system developed by our laboratory.[33] The system uses two wavelengths (785 and 850 nm) to determine the concentration changes of HbO_2 ($\Delta[HbO_2]$) and Hb ($\Delta[Hb]$) based on the modified Beer–Lambert Law. The NIRS probe was supported by a flexible plastic base and held one source and eight detectors, providing eight detector channels. (The channel was defined as the midpoint of the source-detector pair.) Two such NIRS probes were used to cover the left and right PFC. The right probe was placed so that Channel 3 (Ch 3, the midpoint of the NIRS source and Detector 3) was over the F4 electrode, and the line through the source and Detector 3 was parallel to the midline (i.e., the arc from the nasion to the inion). The left probe was placed symmetrically (Fig. 2). The distance between the source and the detector was 3 cm. To estimate the measured brain region, we first determined the corresponding (i.e., the nearest) electrode in the 10–5 system[34] for each NIRS detector channel. Then, based on the standard electrode coordinates for the 10–5 system, we projected all corresponding electrodes to the standard Montreal Neurological Institute (MNI) space using the probabilistic estimation method.[35] Finally, we estimated the measured brain region according to the MNI coordinates of all these corresponding electrodes. Thus, we presumed that the NIRS probes covered part of the bilateral dorsolateral prefrontal cortex (DLPFC) and the ventrolateral prefrontal cortex (VLPFC) in this study. The time resolution was 70 Hz.

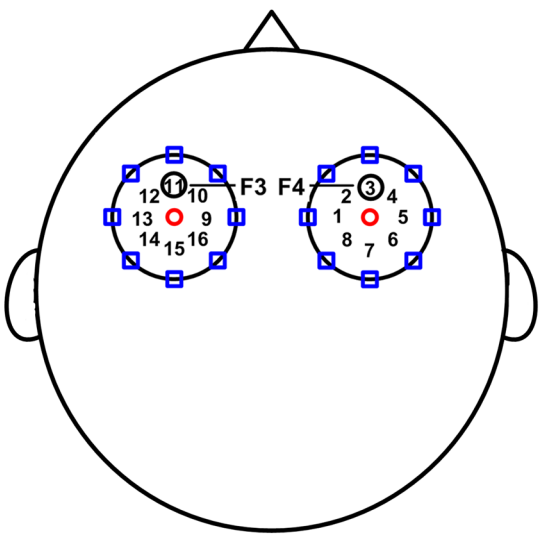

Fig. 2 Schematic of near-infrared spectroscopy (NIRS) measurement channel locations on the head. The red circle indicates the NIRS light source and the blue rectangle indicates the detector. The number (1 to 16) denotes the NIRS detector channel (midpoint of the source-detector pair). Channels 3 and 11 were over F4 and F3, respectively.

2.5 *EEG Recording*

EEG recordings from 18 scalp sites (F3/Fz/F4, FC3/FCz/FC4, C3/Cz/C4, CP3/CPz/CP4, P3/Pz/P4 and PO3/POz/PO4) and the left mastoid were made using a Neuroscan 64-channel device (Synamps[2]), with the right mastoid as reference. Four additional bipolar electrodes were used to record the electro-oculograms (EOGs). The horizontal EOG was recorded by placing two electrodes lateral to the left and right orbits, and the vertical EOG was recorded by placing two electrodes in the superior and inferior areas of the left orbit. The EEG and EOG data were band-pass filtered at 0.05 to 100 Hz, notch filtered at 50 Hz and continuously recorded at a sampling rate of 500 Hz. Electrode impedances were kept below 5 kΩ.

2.6 *Data Analyses and Statistics*

2.6.1 *Behavioral data*

Trials with no responses were rare (mean missed trials: <1 for both stimulus conditions) and were not included in the behavioral data analyses. Only trials with correct responses were used for the response time (RT) analysis, and trials with RTs >3 SD above the mean values were excluded from the analysis (1.11%). Repeated-measures analysis of variance (ANOVA) for RT and error rate were performed with the Condition (neutral, incongruent) and Run (Run 1, Run 2, Run 3, and Run 4) as within-subject factors.

2.6.2 *NIRS data*

The raw optical data were low-pass filtered at 3 Hz (least-squares FIR filter with zero-phase distortion; order: 50), down sampled to 10 Hz, and converted to change in optical density (ΔOD) values. The ΔOD was band-pass filtered with a frequency range from 0.015 to 0.5 Hz to eliminate slow drifts and arterial pulse oscillations, and then converted to hemodynamic parameters ($\Delta[HbO_2]$ and $\Delta[Hb]$) using the differential path-length factor (DPF) method. The DPF values we used were 6.0 at 785 nm and 5.2 at 850 nm.[33] The wavelet minimum description length detrending algorithm was used to suppress unknown global trends in the hemodynamic parameters.[36] Blocks contaminated by movement artifacts were removed from the analyses. Then, for each subject, the hemodynamic parameters were block averaged for each task condition separately.

Because the HbO_2 signal has a higher amplitude and a better signal-to-noise ratio than the Hb signal does,[37] the HbO_2 signal was used for the statistical analyses. The mean values of the HbO_2 signal of the baseline (the last 5-s rest before the task) and the task (5 to 20 s after the task beginning) were computed for each subject, channel, and task condition. The difference in the mean values of the HbO_2 signal between the task and the baseline was used to indicate the hemodynamic response to each task condition. The hemodynamic responses of

incongruent and neutral tasks were compared using paired *t*-tests in a channel-wise manner, and a false discovery rate (FDR) control was used for these channel-wise *t*-tests.

2.6.3 *EEG data*

The EEG data were re-referenced to the average of the left and right mastoid data. Movement artifacts were identified and removed by visual inspection, and eye-blink artifacts were corrected using a regression approach. The EEG data were then low-pass filtered at 40 Hz. Filtered EEG data were segmented into 1200-ms epochs, including a 200-ms prestimulus baseline. Only epochs with correct button presses were included. After the baseline correction, epochs contaminated with artifacts (the threshold for artifact rejection was $\pm 80\ \mu$V) were rejected. Then, epochs were averaged separately for the two types of stimuli.

Based on our results and previous studies, analyses focused on N450 and LPC. Conflict has to be detected and resolved before the behavioral response to incongruent stimuli occurs.[20,38] Thus, to better understand the cognitive processes N450 and LPC reflect, mass univariate analyses were first used to reveal the time intervals showing significant Stroop effects and determine whether the evident N450/LPC Stroop effect occurred before or after the behavioral response to incongruent stimuli. Mass univariate analysis is an approach to analyze data by performing a massive number of univariate hypothesis tests (e.g., *t*-tests). Then, to compare our results with those of the previous studies and examine the interaction between Condition and other factors, ANOVA was used to analyze N450 and LPC.

For mass univariate analyses, a paired *t*-test was performed on each point of the time-cortical site matrix to reveal the time range that showed a significant difference between incongruent and neutral stimuli. Time points from 400 to 1000 ms after the stimulus onset were analyzed. For multiple comparisons, no correction was used in order to avoid influencing the judgment of whether the evident N450/LPC Stroop effect occurred before or after the behavioral response. For the ANOVA, time windows of 450 to 650 and 880 to 1000 ms were chosen for N450 and LPC based on the results of mass univariate analyses at each electrode. The mean amplitudes for N450 and LPC were obtained for each electrode in the six regions: frontal (F3, Fz, F4), frontocentral (FC3, FCz, FC4), central (C3, Cz, C4), centroparietal (CP3, CPz, CP4), parietal (P3, Pz, P4), and occipitoparietal (PO3, POz, PO4). Repeated-measures ANOVA with Condition (neutral, incongruent), Region (frontal, frontocentral, central, centroparietal, parietal, occipitoparietal), and Laterality (left, middle, right) as within-subject factors were performed on the mean amplitudes of N450 and LPC. Because the Stroop effect was the primary interest of this study, only significant main effects and interactions involving the factor Condition were reported.

2.6.4 *Correlation between NIRS and ERP data*

The results of mass univariate analyses showed that the significant N450 Stroop effect occurred before the behavioral response to incongruent stimuli, while the significant LPC Stroop effect occurred after it (see the third paragraph of Sec. 4). These results indicated that only N450 was associated with conflict processing before the behavioral response. Thus, we analyzed the relationship between N450 and HbO_2. Because the conflict-related processing was the focus of this study, the Stroop effect was used as an index in the relationship analysis.

Previous studies have shown that task-related electrophysiological and hemodynamic responses might be correlated.[26,39] Therefore, Pearson's correlation coefficient was used to examine the relationship between HbO_2 and N450. In addition, the correlation between the hemodynamic response and the electrophysiological response in different time windows might provide information about the latency at which one brain region processes information.[27] We further examined the correlation between the ERP Stroop effect for each 20-ms bin during the period from 400 to 700 ms after the stimulus onset and the HbO_2 Stroop effect.

Statistical Package for the Social Sciences 13 software was used for all statistical analyses except the Stroop effect analysis of NIRS data. The level of significance for statistical analyses was set at $p < 0.05$. The Greenhouse–Geisser correction was applied to adjust the degrees of freedom of the F ratios where necessary, and the Bonferroni correction was used for multiple comparisons unless otherwise specified.

3 Results

3.1 *Behavioral Results*

Figure 3 displays the average RT and error rate for each run. Regarding RT, the repeated-measures ANOVA revealed a significant Condition effect [$F(1,14) = 41.133$, $p < 0.001$, $\eta_p^2 = 0.746$], suggesting a longer RT for the incongruent

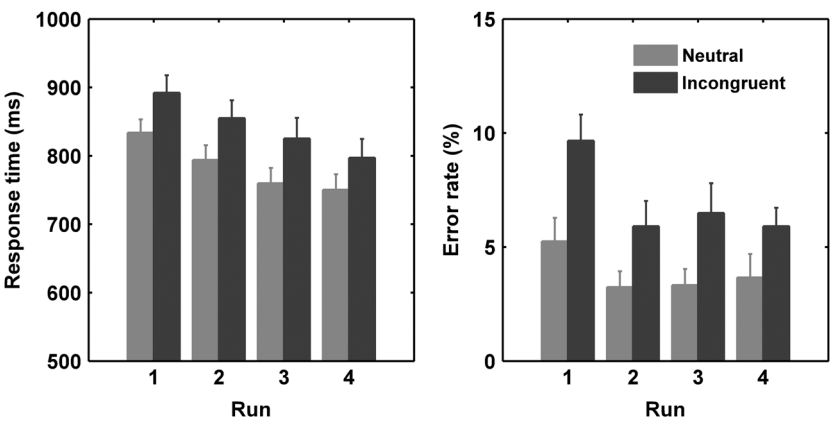

Fig. 3 Response time and error rate for each run. The data are shown as mean ± standard error (SE).

condition compared with the neutral condition. There was a significant Run effect [$F(1.964, 27.493) = 23.62$, $p < 0.001$, $\eta_p^2 = 0.628$]. Follow-up multiple comparisons showed that the RT order was Run 1 > Run 2 > Run 3 ≈ Run 4. Regarding the error rate, the repeated-measures ANOVA disclosed a significant Condition effect [$F(1, 14) = 42.857$, $p < 0.001$, $\eta_p^2 = 0.754$], indicating a higher error rate for the incongruent condition. The ANOVA also revealed a significant Run effect [$F(3, 42) = 8.567$, $p < 0.001$, $\eta_p^2 = 0.38$]. Follow-up multiple comparisons showed that the error rate was higher for Run 1 than for Run 2 and Run 4. Although no significant interaction was observed for either RT or error rate ($p > 0.05$), a paired t-test was used to determine whether the Stroop effect was significant for the RT and error rate in each run. The results showed a significant Stroop effect in each run (RT: $t > 4.84$, $p < 0.001$; error rate: $t \geq 3.062$, $p \leq 0.008$), indicating that the Stroop interference effect remained significant across the entire experiment.

3.2 *NIRS Results*

Figure 4(a) shows the grand average time courses of the HbO_2 responses to neutral and incongruent tasks at one typical channel (Ch 9). The statistical analyses revealed significant Stroop effects in all eight channels for the left PFC (Ch 9 to 16) and in three channels for the right PFC (Ch 2/6/7; $p < 0.05$, FDR correction), indicating greater HbO_2 concentration increase for the incongruent task than for the neutral task. Figures 4(b) and 4(c) show the maps of t-values from the Stroop effect tests for the left and right PFC, respectively. According to the effect size analyses, the Stroop effects were larger in the left PFC than in the right PFC, with the largest Stroop effect at Ch 9 (Cohen's $dz = 1.667$).

3.3 *ERP Results*

Figure 5 shows the average ERP waveforms for neutral and incongruent stimuli at the six midline electrodes.

The mass univariate analyses revealed significant differences between incongruent and neutral stimuli during two distinct time windows (422 to 680 and 870 to 1000 ms) in the six regions. The ERP elicited by incongruent stimuli was more negative during the 422 to 680-ms period and more positive during the 870 to 1000-ms period compared with the neutral stimuli.

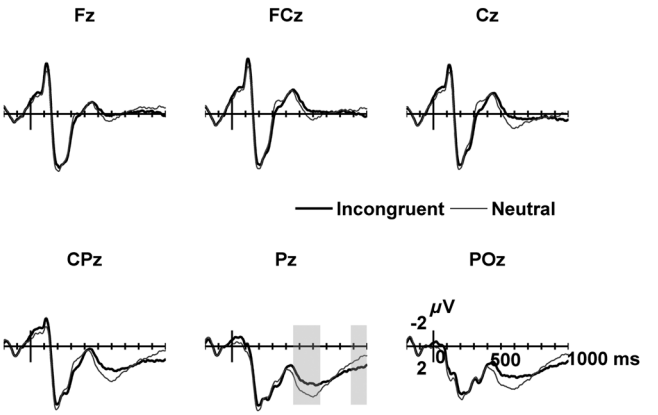

Fig. 5 The grand average of the event-related potential (ERP) waveforms for neutral (blue) and incongruent (red) stimuli at the six midline electrodes. The gray bars at Pz indicate the time windows used in the analysis of variance for N450 (left) and late positive complex (right).

3.3.1 *N450 (450 to 650 ms)*

The ANOVA revealed a significant Condition effect [$F(1, 14) = 16.001$, $p = 0.001$, $\eta_p^2 = 0.533$], indicating a more negative N450 response for the incongruent condition. The Condition × Region interaction was evident [$F(1.446, 20.248) = 3.963$, $p = 0.047$, $\eta_p^2 = 0.221$]. Further simple effect analyses showed that the Stroop effect was significant at each region (Table 1). No other interactions involving Condition were significant ($p > 0.05$).

Table 1 The statistical results of the N450 Stroop effect at each region.

N450	*F*	*P*	η_p^2
Frontal	7.41	0.017	0.336
Frontocentral	8	0.013	0.364
Central	10.71	0.006	0.434
Centroparietal	18.2	0.001	0.565
Parietal	21.67	<0.001	0.607
Occipitoparietal	12.49	0.003	0.471

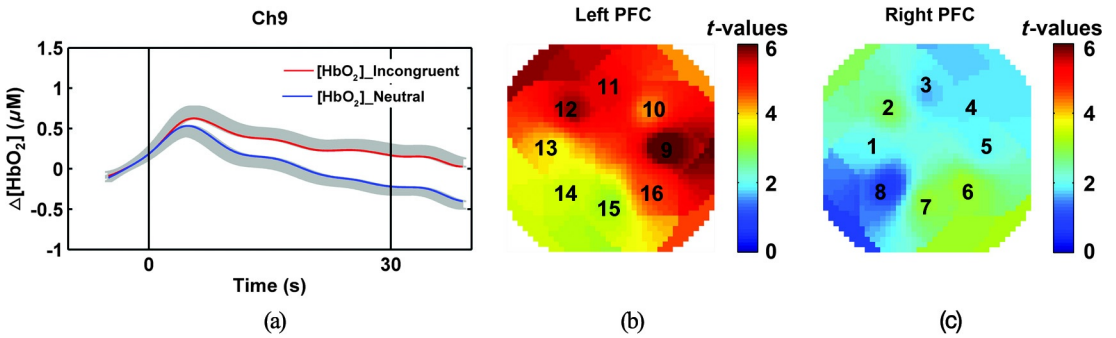

Fig. 4 (a) The grand average time courses of HbO_2 responses to neutral (blue) and incongruent (red) tasks at typical Channel 9 (Ch 9). The gray region indicates SE. The black lines at 0 and 30 s indicate the start and end of the task blocks. (b) and (c) show the t-values from the Stroop effect tests for the left and right PFC, respectively.

Table 2 Correlation between HbO_2 Stroop effects and N450 Stroop effects in the centroparietal and parietal regions.

	Centroparietal	Parietal
Ch 2	−0.48[b]	−0.523[a]
Ch 6	−0.148	−0.241
Ch 7	−0.38	−0.448[b]
Ch 9	−0.654[a]	−0.537[a]
Ch 10	−0.592[a]	−0.449[b]
Ch 11	−0.541[a]	−0.41
Ch 12	0.131	0.221
Ch 13	−0.166	−0.14
Ch 14	−0.113	−0.144
Ch 15	−0.174	−0.206
Ch 16	−0.57[a]	−0.453[b]

[a]Significant correlation ($p < 0.05$).
[b]Marginally significant correlation ($p < 0.1$).

3.3.2 *LPC (880 to 1000 ms)*

The ANOVA disclosed an evident Condition effect [$F(1,14) = 10.609$, $p = 0.006$, $\eta_p^2 = 0.431$], indicating a more positive LPC response for the incongruent condition. The Condition × Laterality interaction was significant [$F(2,28) = 3.751$, $p = 0.036$, $\eta_p^2 = 0.211$]. Simple effect analyses revealed that the Condition effect was significant for the left, middle, and right cortical sites ($p < 0.05$), with the largest Condition effect at the left cortical sites indicated by the largest effect size (left: $\eta_p^2 = 0.474$; middle: $\eta_p^2 = 0.400$; right: $\eta_p^2 = 0.370$). No other interactions involving Condition were significant ($p > 0.05$).

3.4 *Correlation Between HbO_2 and N450*

Since it is difficult to determine the neural generator source location from the ERP scalp voltage distribution, the largest N450 Stroop effect was correlated to the HbO_2 Stroop effect. The larger effect size (η_p^2) indicated that the N450 Stroop effects were greater in centroparietal and parietal regions than in the other four regions. Thus, the N450 in the centroparietal and parietal regions was used to correlate with HbO_2. The N450 Stroop effect in the centroparietal (parietal) region was obtained by averaging the data from the three electrodes in that region, and then correlated with the significant HbO_2 Stroop effect (left PFC: Ch 9 to 16; right PFC: Ch 2/6/7).

The N450 Stroop effect in the centroparietal region was significantly negatively correlated with the HbO_2 Stroop effects in the left PFC (Ch 9/10/11/16; r ranged from −0.541 to −0.654, $p < 0.05$). The N450 Stroop effect in the parietal region was significantly negatively correlated with the HbO_2 Stroop effects in the left (Ch 9; $r = -0.537$, $p < 0.05$) and right PFC (Ch 2; $r = -0.523$, $p < 0.05$) (Table 2). Due to the negativity of N450, this negative correlation indicated that the larger the difference in the N450 amplitude between these two stimulus conditions, the greater the difference in the HbO_2 signal. To explore whether the HbO_2 responses in the left and right PFC were correlated with the N450 at different time ranges, the correlation between the HbO_2 Stoop effect and the ERP Stroop effect for each 20-ms bin from 400 to 700 ms after the stimulus onset was further examined. These analyses revealed that the HbO_2 Stroop effect in the left PFC (Ch 9/10/16) was negatively correlated with the N450 Stroop effect during the early phase (from 440 to 580 ms; Fig. 6), and the HbO_2 Stroop effect in the left (Ch 11) and right PFC (Ch 2) was negatively correlated with the N450 Stroop effect during the later phase (from 600 to 680 ms; Fig. 6).

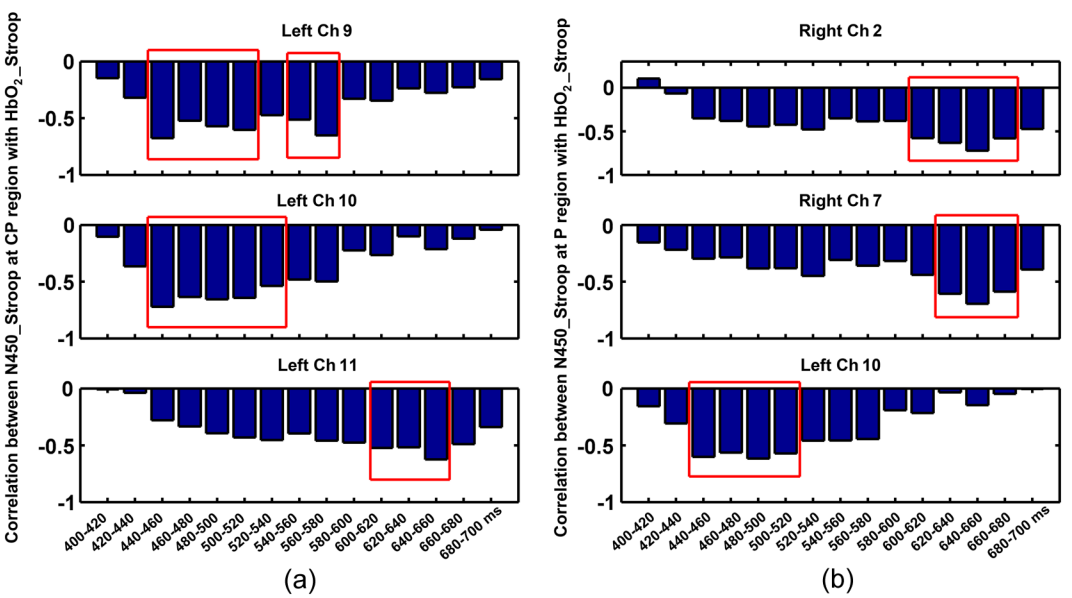

Fig. 6 (a) Correlation coefficients between ERP Stroop effects for each 20-ms bin within 400 to 700 ms at the centroparietal region and the HbO_2 Stroop effects at Ch 9 (left top), Ch 10 (left middle), and Ch 11 (left bottom). (b) Correlation coefficients between ERP Stroop effects for each 20-ms bin within 400 to 700 ms at the parietal region and the HbO_2 Stroop effects at Ch 2 (right top), Ch 7 (right middle), and Ch 10 (right bottom). The red rectangle indicates the time window during which there was a significant correlation between these two Stroop effects ($p < 0.05$).

In addition, the N450 Stroop effect in the centroparietal region was marginally significantly negatively correlated with the HbO_2 Stroop effect in the right PFC (Ch 2; $r = -0.48$, $p < 0.1$). There were also some marginally significant negative correlations between the N450 Stroop effect in the parietal region and the HbO_2 Stroop effects in the left (Ch 10: $r = -0.449$, $p < 0.1$; Ch 16: $r = -0.453$, $p < 0.1$) and right PFC (Ch 7; $r = -0.448$, $p < 0.1$; Table 2). Further analyses of the marginally significant correlation between HbO_2 and N450 also proved that HbO_2 in the left PFC (Ch 10/16) was correlated with the early phase of N450 (Fig. 6), and HbO_2 in the right PFC (Ch 2/7) was correlated with the later phase of N450 (Fig. 6).

4 Discussion

In this study, we examined the relationship between the conflict-related hemodynamic signal in the PFC and the electrophysiological signal during a Chinese color-word matching Stroop task. There were significant Stroop effects in behavioral (RT, error rate), NIRS (HbO_2), and ERP (N450, LPC) data, consistent with the previous studies.[5,16,17] Furthermore, the HbO_2 Stroop effect was negatively correlated with the N450 Stroop effect. More specifically, the HbO_2 Stroop effect in the left PFC (Ch 9/10/16) was negatively correlated with the N450 Stroop effect during the early phase (440 to 580 ms), while the HbO_2 Stroop effect in the bilateral PFC (left: Ch 11; right: Ch 2/7) was negatively correlated with the N450 Stroop effect during the later phase (600 to 680 ms).

The color-word matching Stroop task was used because this task mainly activates the lateral PFC.[5,13] In the present study, the HbO_2 response in the bilateral PFC was stronger for the incongruent stimulus task than for the neutral stimulus task, which is consistent with the previous studies reporting the involvement of the bilateral PFC in the Stroop task.[5,40,41]

The N450 amplitude was more negative and the LPC amplitude was more positive for incongruent stimuli compared with the neutral stimuli, which was consistent with the previous reports.[16,17,21] The significant N450 Stroop effect lasted from approximately 420 to 680 ms after the stimulus onset, and the significant LPC Stroop effect began at approximately 870 ms. The start of the evident LPC Stroop effect was somewhat earlier than the behavioral response to incongruent stimuli in Run 1, but later than the behavioral response to incongruent stimuli in Runs 2 to 4. LPC has been associated with conflict resolution,[22,23] conflict adaption,[24,25] or the re-activation of word meaning.[16,17] Because conflict needs to be resolved before a behavioral response occurs,[20,38] the significant LPC Stroop effect occurring after the behavioral response indicates that the LPC could not be associated with conflict resolution before a manual response. Additionally, the conflict adaption might be greatly diminished under the conditions of our experimental design.[42] Taken together, we suggest that the LPC could be related with word meaning processing.[21,22] Combined with the previous studies, we infer that N450 is related to conflict processing.[16,21] In addition, N450 Stroop effects during the early and later phases were negatively correlated with HbO_2 Stroop effects in the left PFC and the bilateral PFC, respectively. This dissociation of the early and later phases of N450 suggests that there are two stages in N450. Our study supports that N450 reflects both conflict detection and resolution.[16,21]

The negative correlation between N450 and HbO_2 indicates that the larger the difference in the N450 between these two stimulus conditions, the greater the difference in the HbO_2 signal. Previous animal studies have suggested a tight coupling between the hemodynamic response and the local field potential (LFP).[43,44] The LFP is known to be the basis of scalp EEG/ERP,[45] implying that the spatiotemporal data integration can be obtained by examining the correlation between the hemodynamic response and the scalp EEG/ERP in most situations. In addition, human studies have also shown that these two types of measures were correlated during brain function.[26,39] Our results fit well with the previous studies that show a coupling between these two measures. The correlation suggests that N450 and activity in certain PFC regions reflect related processing.

The HbO_2 Stroop effect in the left PFC (Ch 9/10/16, located approximately in the left DLPFC) was negatively correlated with the N450 Stroop effect during the early phase. The early phase of N450 corresponded with conflict detection. Although some studies have suggested that the ACC detected conflict,[6,12] others have suggested that the ACC was associated with response-related processing, but not conflict-related processing.[13,46] Given that the ACC activity was not observed in the color-word matching Stroop task,[13] this correlation indicated that the left PFC might be involved in conflict detection. Considering the bidirectional connection between the DLPFC and posterior brain regions,[47] and the involvement of the left middle frontal gyrus in Chinese semantic processing,[48] it is reasonable to conclude that the left DLPFC plays a role in detecting conflict. Furthermore, there is increasing evidence supporting the assumption that the DLPFC can detect conflict. Milham et al. found that practice had different influences on the ACC and the left DLPFC.[8] While the ACC activity existed only during the first two cycles, the left DLPFC activity persisted even until the last two cycles (Cycles 5 to 6). Milham et al. suggested that the DLPFC could detect the nonresponse conflict independent of the ACC.[8] Morishima et al. reported that the left DLPFC activity covaried with the neutral activity of sensory conflict for incongruent trials in a face-word Stroop task, suggesting the left PFC's role in detecting conflict.[14] Some lesion studies in patients and animals also suggested that the ACC was not necessarily involved in conflict processing,[15,49] while DLPFC was involved in conflict detection.[9,15,50] Given our findings and those of the previous studies, we suggest that the left PFC is involved in conflict detection.

The HbO_2 Stroop effect in the bilateral PFC was negatively correlated with the N450 Stroop effect during the later phase. This correlation supports the generally accepted viewpoint that the PFC is involved in conflict resolution. The PFC exerts the cognitive control to resolve conflict by favoring the processing of task-relevant information and/or inhibiting the processing of task-irrelevant information.[51,52] Participation of both the left and right PFC in conflict resolution has been proven in many previous studies.[11,40,41]

NIRS measures the hemodynamic response and indirectly reflect neural activity at a reasonable spatial resolution, while ERP measures the electrical response and directly reflect neural activity at a high temporal resolution. Our study shows that the analysis of the relationship between these two complementary responses can not only provide information about the processing stage in which one brain region is involved, but also distinguish the different processing stages in the ERP response with the help of brain activity.

This study examined the relationship between hemodynamic and electrophysiological signals to investigate the neural

correlates of conflict processing in a Chinese color-word matching Stroop task. The significant LPC Stroop effect occurring after the behavioral response to incongruent stimuli suggests that the LPC is associated with the re-activation of word meaning. The evident N450 Stroop effect occurred before the behavioral response to incongruent stimuli. Besides, the N450 Stroop effects during the early and later phases were negatively correlated with HbO_2 Stroop effects in the left PFC and in the bilateral PFC, respectively. These results indicate the following: (1) there are two stages in N450: conflict detection and resolution; (2) the left PFC may be involved in conflict detection and the bilateral PFC is engaged in conflict resolution. Our study promotes the understanding of the neural correlates of conflict processing and shows that an analysis of the correlation between hemodynamic and electrophysiological measures can be an effective method for studying human brain function.

Acknowledgments

We would like to thank all subjects for their participation. We thank Qianzhu Luo for proofreading the manuscript. This study was supported by the Science Fund for Creative Research Group of China (Grant No. 61121004), National Natural Science Foundation of China (Grant No. 61078072), and 863 Program (Grant No. 2012AA011602).

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