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Research Report
Brain mechanism of Stroop interference effect in Chinese characters
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ABSTRACT

Event-related brain potentials were measured when 11 healthy Chinese subjects finished Chinese Characters Stroop tasks. The behavioral data showed that the Stroop task yielded a robust Stroop interference effect as indexed by longer RT for incongruent than congruent color words. Scalp ERP analysis revealed the neurophysiological substrate of the interference effect: a greater negativity in the incongruent as compared to the congruent was found between 350 and 550 ms poststimulus over midline fronto-central scalp regions. Dipole source analysis (BESA software) of the difference wave (incongruent–congruent) indicated that a generator localized in prefrontal cortex (PFC) contributed to this effect, possibly related to conflict processing and response selection. The results provided electrophysiologic evidences of the brain and cognitive mechanism of Stroop interference effect in Chinese characters and suggested that the difference between Chinese characters and English words had influence on temporal patterns of the Stroop interference effect.

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1. Introduction

The Stroop interference effect (or the Stroop effect) refers to an increase in response time observed when the word meaning and the stimulus hue do not match. For example, in an incongruent condition, the word “green” is presented in the color red whereas in a congruent condition the word “red” is presented in the color red. The time measured between exposure to the word and completion of the verbal response is typically greater in the incongruent condition (Stroop, 1935). The Stroop test has been utilized by researchers to explore the nature of automatic and controlled cognitive processes (Henik, 1996; Posner et al., 1975), disturbances in cognition resulting from various psychiatric and/or neurological disorders (Rafal et al., 1994), the neurocognitive architecture of

selective attention (Rebai et al., 1997), and age-related decline in inhibitor processing (West and Alain, 2000). Stroop test results have led to the inception of five predominant models of cognitive processing: the relative speed process model, the automatization model, the perception encoding model, the parallel processing model, and the parallel distributed processing model (Cohen, 1990; Logan, 1980; Macleod, 1991; Qian and Li, 2003).

Results of Positron Emission Tomography (PET) and functional magnetic resonance imaging (fMRI) indicate that the area of the brain that shows the most robust activation during performance of the Stroop color naming task is the anterior cingulate cortex (ACC), including the ventral subgenual, rostral, and dorsal regions. Additional areas of the brain that show increased activation include the prefrontal

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cortex (PFC), motor cortex, inferior temporal gyrus, and superior and inferior parietal cortex (Carter et al., 1995; Ardi and Peter, 2002). Measurement of event-related potentials (ERPs) provides better temporal resolution of neural activity than do PET and fMRI, thereby making ERPs a favorable measure for examining the neural processing that occurs in the time between stimulus presentation and response in the Stroop task.

In general, P300 ERP latency has been shown to vary with the duration of perceptual processes, but is insensitive to the duration of motor processes (Donchin and Coles, 1988). Therefore, the P300 ERP may be used to test the hypothesis that the Stroop interference effect originates from response-rather than stimulus-related processing. In addition, ERP amplitude reflects the amount of attentional resources employed in a given task, thus providing information about differing amounts of mental effort required for various color/meaning pairings. Thus, the P300 ERP can provide considerable insight into Stroop phenomena because it provides independent measures of stimulus evaluation time and attentional requirements (Ilan and Polich, 1999).

Ilan and Polich (1999) found no relationship between response time (RT) and P300 ERP latency, which was taken to indicate that the Stroop interference effect occurs in the response selection stage and not in the stimulus detection or evaluation stages of cognitive processing. However, West and colleagues found that a greater positive wave (P500) was evoked in the incongruent condition over the fronto-polar region of the brain and, within 500–1000 ms, a greater negative wave was evoked over the fronto-central region. The authors concluded that these components probably reflected “conflict discovery and conflict resolution processes” (West and Alain, 1999). Liotti et al. (2000) found that a negative wave appeared over the medial dorsal region between 350 and 500 ms poststimulus, with the peak at 410 ms. Dipole source analysis suggested that an independent generator present in the anterior cingulate cortex was mainly related to conflict discovery and conflict resolution. Between 500 and 800 ms poststimulus, a prolonged positive wave developed over the left superior temporo-parietal scalp that was apparently related to word meaning processing. Recently, Markela-Lerenc et al. (2004) found greater negativity in the incongruent than in the congruent condition over left fronto-central scalp regions in a time frame of 350 and 450 ms after the stimulus presentation. Source analysis of the difference wave (incongruent–congruent) indicated that a generator localized in the left prefrontal cortex (PFC) contributed to this effect. Immediately after this first effect (between 450 and 550 ms after stimulus presentation), a greater positive potential developed over midline fronto-central scalp regions in the incongruent than in the congruent condition. A generator of this effect appeared to be located in the right anterior cingulate cortex (ACC). The ACC activation seemed to follow the activation of the PFC with some overlap between the two components. One possible interpretation of this finding is that the PFC signals the ACC when executive control is required and the ACC implements the control.

The results reported by Liotti and West and Markela-Lerenc and colleagues demonstrated two modulations of

the ERPs that are consistently associated with conflict processing in the Stroop task: the N450 wave and the sustained potential (Liotti et al., 2000; Markela-Lerenc et al., 2004). The N450 peaks between 400 and 500 ms after stimulus onset and reflects a phasic fronto-central negativity that differentiates incongruent trials from congruent and neutral trials. This ERP component seems to be related to response detection and may arise from activity in prefrontal areas. The sustained potential is elicited about 500 ms after stimulus onset and reflects a sustained parietal positivity-lateral frontal negativity. Activity in lateral-frontal and extrastriate areas has been reported to generate the sustained potential. However, some disagreement remains over the brain structures and cognitive processing stage involved in the Stroop interference effect.

Biederman and Tsao (1979) discovered that a greater interference appeared for Chinese characters in Chinese subjects than for English words in English subjects. They suggested that there may be some fundamental differences in the perceptual demands of reading Chinese and English. Tsao and Wu (1981) reported that a greater interference occurred for Chinese subjects when color words were presented to the right hemisphere of the brain while a greater interference occurred for English subjects when the color word was presented to the left hemisphere. These results suggest that the process of Chinese word identification and naming may involve particular neural networks associated with its unique pictographic nature. Some studies have found that more right hemisphere cortical regions were involved in reading Chinese relative to reading English (Dong et al., 2005; Tan et al., 2001). This is attributed to the square shape of the logograph which requires an elaborate analysis of the spatial information and locations of various strokes comprising the logographic character. Kochunov et al. (2003) also found neuroanatomical differences between Chinese speakers and English speakers that were mainly limited to gyri in the frontal, temporal, and parietal lobes.

In addition, recently, studies about the visual word recognition suggested that there are some differences between alphabetic systems (e.g., English) and ideographic systems (e.g., Chinese) (Plaut et al., 1996; Van Orden et al., 1988; Zhou and Marslen-Wilson, 2000; Zhou et al., 1996). For English words, phonological activation from orthography is indeed more efficient than semantic activation from orthography because there is in general a systematic mapping between orthography and phonology, whereas the relations between orthography and semantics are mostly arbitrary (Plaut et al., 1996; Van Orden et al., 1988). Unlike English words, a Chinese character has a direct association with its meaning because Chinese language is composed of ideographic scripts and is based on the association of meaningful morphemes with graphic units (Zhou and Marslen-Wilson, 2000; Zhou et al., 1996). That is to say, Chinese characters recognition may be strictly a visual form-to-meaning process. The Stroop interference effect can be explained in terms of differences in the relative strengths of two competing, color and word meaning, pathways. Longer reaction time and greater interference are present when the irrelevant attribute of the stimulus (the word meaning) is analyzed faster (i.e., is more automatic)

Table 1 – Summary of performance data

	Congruent	Incongruent	Neutral
Mean RT (ms)	624 (65)	716 (81)	658 (70)
Corrects (%)	97 (1.9)	92 (6.8)	96 (2.7)

Mean and standard deviation for reaction times (RT) and mean percent corrects for different Stroop task conditions.

than the relevant attribute (color), and the unwanted response is therefore available first (Cohen, 1990). Thus, we anticipate that there might be different temporal patterns of brain activation during performance of the Stroop Chinese color–word if the time course of semantic activation in Chinese characters recognition was different from that of English words.

However, there was a paucity of studies about the brain mechanism of the Stroop interference effect in Chinese characters. When subjects finish the color naming task in two different conditions (in Chinese characters and in English word), a further study is required to reveal whether the difference between the mental mechanism and the physical mechanism existed in the Stroop interference effect. Recently, Peng et al. (2004) studied the Stroop interference effect in sixth grade children using Chinese characters. They found that the first ERP effect was obtained at about 300 ms poststimulus onset. The P300 amplitude induced by the incongruent condition was larger than that in the congruent condition, while the P300 latency for incongruent trials was the slowest. The second effect generated by color words was a slow wave emerging

at about 400 ms (P400–600) after the stimulus onset in the parietal scalp region. This suggested that the interference effect was the result of processing during the early stimuli evaluation stage and later response stage. Results of this study, using children for subjects, were inconsistent with results of related research; however, the conclusion that Chinese adults have a different temporal pattern of brain activation during the Stroop task using Chinese characters compared to English words could not be drawn.

The aim of our study was to investigate spatio-temporal patterns of brain activation during performance of the Stroop Chinese color–word task using high-density (64 channels) ERP recording and dipole source analysis. First, we wanted to know which modulations of the ERPs are consistently associated with conflict processing in the Chinese Character Stroop tasks (i.e., P300, N450 and sustained potential). Second, in the process of word identification and word naming for Chinese speakers, we anticipated that there might be some interesting findings about which brain areas are involved in the Stroop task because the neural mechanism for semantic activation in Chinese characters recognition might be different from English words.

2. Results

2.1. Behavioral data

In the mean reaction time analysis (see Table 1), a very robust Stroop color–word interference effect was obtained as indicated by longer mean RTs for the incongruent than congruent or neutral stimuli ($F(2,20) = 45.9, P < 0.001$). Post

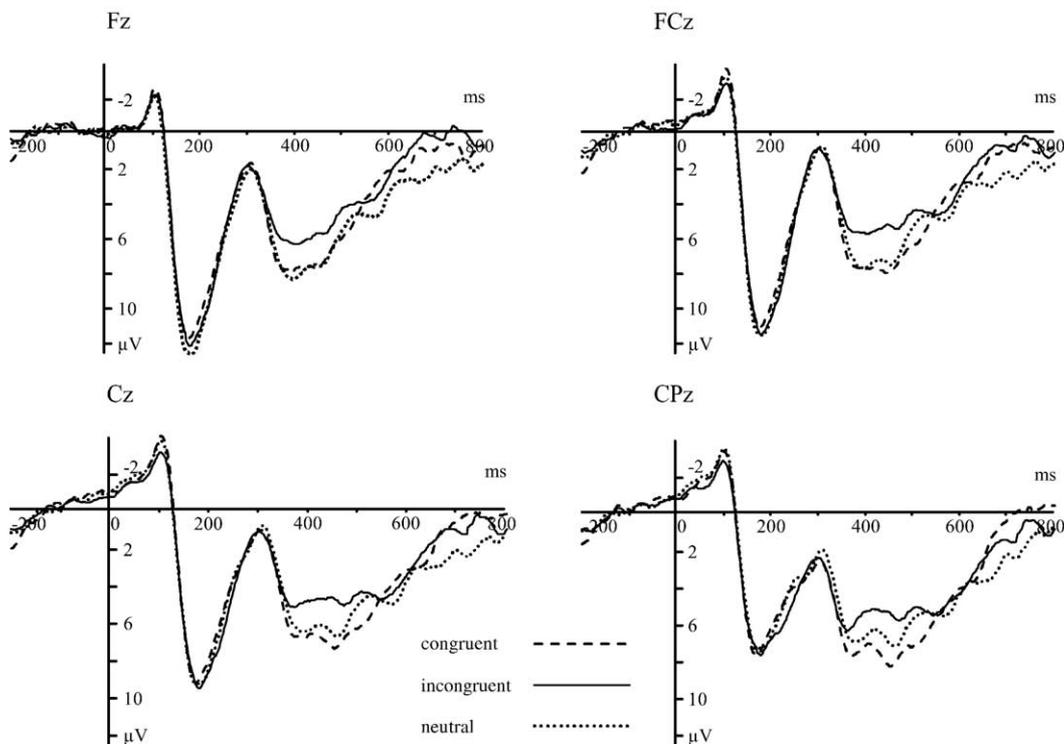


Fig. 1 – Grand average ERPs at Fz, FCz, Cz, and CPz for all conditions.

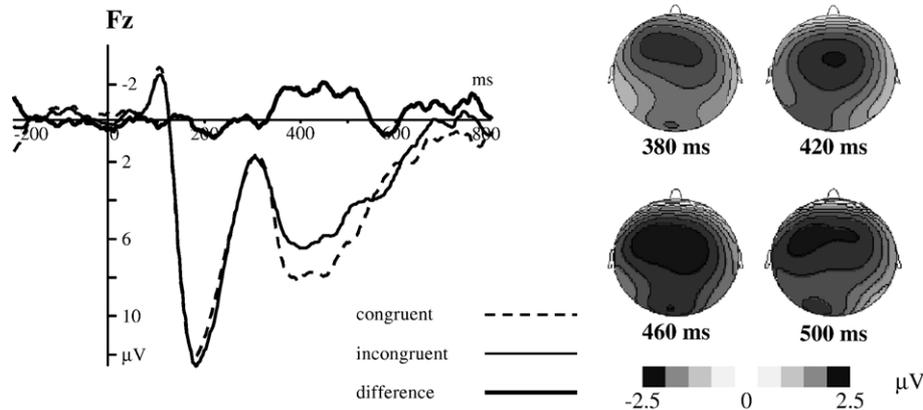


Fig. 2 – (Left) Grand average ERP to congruent and incongruent conditions and the difference wave (incongruent–congruent) at Fz. (Right) Topographical maps of the voltage amplitudes for the incongruent vs. congruent condition difference wave in the 380 ms, 420 ms, 460 ms, and 500 ms.

hoc tests revealed significantly longer RTs in the incongruent than congruent ($P < 0.001$, mean effect size 92 ms) and neutral ($P < 0.05$, mean effect size 58 ms) condition. For the accuracy data, task type was significant ($F(2,20) = 6.08$, $P < 0.05$). Simple mean effects revealed significantly more errors for incongruent than congruent and neutral conditions ($P < 0.05$), and no difference for congruent condition vs. neutral condition.

2.2. Electrophysiological scalp data

The grand-average map in three conditions (Fig. 1) and topographic maps of difference wave incongruent vs. congruent (Fig. 2) showed the following spatio-temporal distribution for the ERP data. A greater negativity to the incongruent than to the congruent in the 350–550 ms time window over fronto-central scalp regions was mainly observed. Mean amplitudes in the time window of 350–550 ms and 550–700 ms were analyzed using two-way repeated-measures ANOVAs.

Table 2 shows the results of the ANOVAs for each of the time windows examined. The strongest effects were in the 450–500 ms window. There was a main effect of stimulus type ($F(2,20) = 3.75$, $P < 0.05$). Mean amplitude was more negative for the incongruent than for the congruent condition ($P < 0.01$). In addition, the interaction stimulus type and electrode location were not significant. Three

stimulus types evoked a later positive component in the later 550–700 ms time window, but there was no significant difference both in the stimulus type and electrode location, as well their interaction.

2.3. Dipole source analysis

The source analysis using BESA software was performed on the ERP difference wave of the incongruent and congruent conditions. PCA was employed in the 450–500 ms time window. PCA indicated that two principal components were needed to explain 96.0% of the variance in the data. The second component explained only 3.8% of the variance; therefore, one dipole was fitted with no restriction to the direction and location of dipole. The result indicated that this dipole located approximately in the prefrontal cortex (location according Talairach coordinates: $x = -4.8$, $y = 50.3$, $z = 34.8$) and revealed maximal dipole moment strength at about 450 ms. This model explained the data best and accounted for most of the variance with a residual variance (RV) of 13.2% at the peak activity of this dipole (Fig. 3). The display of the residual maps showed no further dipolar

Table 2 – Summary of results for the ANOVAs on the Stroop effect for the 350–400, 400–450, 450–500, 500–550, and 550–700 ms time windows

Time (ms)	Task		Task × electrode site	
	F	P	F	P
350–400	1.26	ns	0.73	ns
400–450	2.07	ns	0.83	ns
450–500	3.75	0.04	0.78	ns
500–550	1.26	ns	0.85	ns
550–700	0.85	ns	1.15	ns

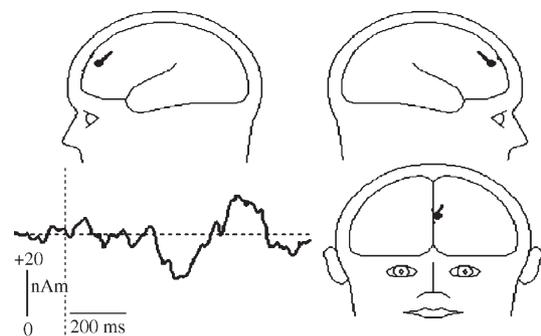


Fig. 3 – Results of the dipole source analysis of the difference wave (incongruent vs. congruent). The left-bottom shows the source activity waveforms, whereas the right figure displays the mean locations of the dipole. The dipole is located approximately in the prefrontal cortex ($x = -4.8$, $y = 50.3$, $z = 34.8$).

activity and no further dipoles could be fitted in the investigated time window.

3. Discussion

In the present study, robust behavioral and electrophysiological effects of color–word interference were seen in Chinese subjects performing the Chinese characters Stroop task, supporting evidence for the universality of the Stroop interference effect and further supporting the idea that the interference is related to the judgment of words calligraph color (Magiste, 1984; Sumiya and Healy, 2004). More importantly, comparison of ERPs elicited by the incongruent condition to those elicited by the congruent condition revealed a continuous negative component (N450) ranging from 350 to 550 ms, which was mainly distributed over fronto-central scalp regions. Dipole source analysis suggests that this negative component was generated in the PFC, which was probably related to conflict processing and response selection.

In comparing these with previous findings (Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003), it seems that Chinese and English Stroop interference effects have consistent time courses, for they both have an obvious negative wave (incongruent–congruent) at first, and topographical maps demonstrated that this negative component is mainly distributed over fronto-central scalp regions. During performance of the Stroop task of color naming of Chinese characters, despite an intentional attempt on the subject's part to attend to the color of words, the information of color and meaning will inevitably bring about conflict in the incongruent condition, due to the automation of the processing of word meaning. Then, activation of the ACC or PFC is required to control irrelevant information inference (semantic information) and make the right judgment according to the information of color. In contrast to the research findings of Peng et al. (2004), in this study, we did not find a P300 effect during the evaluation stage of stimulus onset, possibly because of more automatic processing from the lexical to the semantic level in adults compared to children (Li et al., 2003). Accordingly, the initial stimulus classification does not necessarily evoke a change in ERP in adults. Furthermore, the later effect of interference seen in adults mainly demonstrated the negative component, and not the positive component, suggesting that different cognitive and brain mechanisms are involved in performance of the Stroop task in adults and children. Therefore, the present results supported the hypothesis that Stroop interference arises primarily from response competition between the color and word at the output stage, and not from initial stimulus identification and evaluation (Atkinson et al., 2003; Ilan and Polich, 1999).

Many studies (Kern et al., 2004; Peterson et al., 1999) have reported activation of the ACC and PFC in the Stroop interference color–word task. These reports seemingly assumed that the negative difference wave (incongruent–congruent) would arise from generators in the ACC and PFC. In the present study, while dipole source analysis of the difference wave indicated that a generator localized in the PFC contributed to this effect, there was no apparent activation or involvement of the ACC. These findings are consistent with

those of Markela-Lerenc, who found that the first Stroop-related effect originated from activity generated in the left inferior PFC between 350 ms and 450 ms following stimulus onset (Markela-Lerenc et al., 2004). However, we did not find that the second effect was localized in the right ACC. It seemingly supports the conclusion that PFC was firstly activated under the task of Stroop interference. Many research findings have indicated that PFC activity is mainly related to conflict processing and is required for evaluation execution control, while ACC activity is mainly related to conflict detection and supervision (Bune et al., 2002; Rowe et al., 2000). Three possible reasons may explain why no activation of the ACC was observed in the current study. First, the celerity of the ACC's initial involvement in processing the conflict may be due to the automation of semantic processing of Chinese color words, and this ACC involvement may be overshadowed by the following strong activation of the PFC. Second, neuroimaging studies show that congruent stimuli may evoke activity in ACC. Therefore, activation of the ACC in the incongruent condition may have been obscured by ACC activity in the congruent condition (Carter et al., 1995; Markela-Lerenc et al., 2004). Third, there is evidence that ACC activity is diminished with increasing training on the Stroop task (Bush et al., 1998). Perhaps the task demands were not great enough for detection of ACC activity in the adults studied here.

It is useful to compare the N450 Stroop interference effect with N400 because both share a similar time range and are related to conflict resolution and response selection. N400 is a negative deflection in the ERP, peaking at approximately 400 ms and elicited by words presented in unexpected or inappropriate sentence contexts (Kutas and Hillyard, 1989). The N400 wave is associated with processing of semantic information that is incongruent with semantic expectancy, for example; “He adds some *sugar* to the coffee” vs. “He adds some socks to the coffee” (McPherson and Holcomb, 1999). A negative wave was evoked when the stimulus “socks” was incongruent with the anticipated information “sugar”. Rebai et al. (1997) found a Stroop interference effect peaking at 400 ms that had a similar centro-parietal distribution as the traditional N400, and was in fact interpreted as an N400. However, Liotti and colleagues argued against this conclusion suggesting that Rebai's study employed only a few electrodes that were limited to midline locations and, in view of the different scalp distribution of the interference effect for speech and manual responses found by these authors, an N400 negative deflection is unlikely. Recent research findings (Nakagome and Takazawa, 2001) also indicate that the component of N400 has more than one source, mainly from temporal lobe regions. In the present study, we found that the Stroop-related effect mainly originated from the PFC. Thus, N450 and N400 are likely to be different types of ERPs.

The N2, observed by van Veen and Carter (Veen and Carter, 2002), is a negative wave with a latency of 340–380 ms after target stimuli onset. In the Eriksen flanker task, the N2 was enhanced following presentation of response-incongruent stimuli for conditions that involved high conflict, with the maximal amplitude located at Cz in the fronto-central scalp distribution, and generated by the ACC. van Veen and Carter suggested that an ACC generator of the fronto-central N2 is elicited by response conflict and not by a perceptual conflict. In

the present study, a greater negativity (N450) was found over midline fronto-central scalp regions in the incongruent vs. the congruent context between 350 and 550 ms after stimulus onset. Although N450 shares similarities with N2 in latency and scalp distribution, dipole analysis localized the generator of the N450 in the PFC. In our study, N450 might reflect cognitive processing of conflict and the PFC might be involved in the selection of competing responses (Carter et al., 1998).

Liotti et al. (2000) found that a prolonged positive wave appeared between 500 and 800 ms after stimulus onset over the left superior temporo-parietal scalp, an area that is associated with the reactivation of the meaning of words. Markela-Lerenc and colleagues also found a greater positive potential in the incongruent vs. the congruent condition between 450 and 550 ms after stimulus presentation over midline fronto-central scalp regions, which are associated with the supervision of conflict (Markela-Lerenc et al., 2004). However, the findings of the present study, using Chinese color words as stimulus materials, did not demonstrate this ERP component. We may speculate that this is because Chinese and English are processed by different neural and cognitive mechanisms (Dong et al., 1996; Luo and Wei, 1998). For example, the processing of Chinese color characters may be strictly a visual form-to-meaning process, while the English words may be from graphic forms to phonological forms then to meanings (Van Orden et al., 1988; Zhou et al., 1996). Thus, the Stroop interference effect in Chinese character Stroop task may be only reflected by the N450. Of course, it might be relative to reactivation of the word meaning.

This study investigated spatio-temporal patterns of brain activation during the Stroop Chinese color-word task using scalp and dipole source analysis of ERPs. Scalp ERP analysis revealed the neurophysiological substrate of the interference effect: a greater negativity in the incongruent as compared to the congruent condition was found between 350 and 550 ms after stimulus onset over midline fronto-central scalp regions. Dipole source analysis of the difference wave (incongruent-congruent) indicated that a generator localized in the PFC, possibly related to conflict processing and response selection, contributed to this effect. These results provide electrophysiological evidence of a brain mechanism for the Stroop interference effect in Chinese characters and suggest that Chinese characters are processed using different cognitive and neural mechanisms than those used in processing English words. The N450 component of the ERP is probably an electrophysiological reflection of PFC functioning that reflects the response competition in restraining inhibition caused by irrelevant information. In the future, further studies should be done using both ERPs and fMRI to examine the role of the PFC in cognitive processing of incongruent information, and to determine whether other brain areas are involved in the Stroop Chinese color-word task.

4. Experimental procedure

4.1. Subjects

Eleven healthy undergraduate students at one university in China (age 23 ± 2 , range 21–26, six men, five women) participated in the

study. All subjects who gave written informed consent, right-handed, had no history of current or past neurological or psychiatric illness, and had normal or corrected-to-normal vision and normal color vision as assessed by several basic color tests. In addition, all subjects were paid ¥20.00 at the end of the experiment.

4.2. Stimuli and procedure

The experiment consisted of neutral, congruent, and incongruent stimuli. The congruent stimuli consisted of the four color words (红, 黄, 绿, 蓝) (red, yellow, green, blue) written in the same color in which the stimulus was presented (e.g., the word 红 (red) written in red color). The incongruent stimuli consisted of the same four words with the display color not matching the word meaning (e.g., the word 绿 (green) written in red ink). Each incongruent stimulus appeared in each of the three colors not matching its meaning. In the neutral condition, three no-color words (笔, 球, 表) (pen, ball, watch) were presented in each of the four colors. The size of the Chinese characters was Song Ti No. 28 1.4° (horizontal) \times 1.4° (vertical), and was displayed in the center of a 17-in. screen at random.

Subjects were seated in a semidark room facing a monitor placed at 80 cm distance from the eyes. They were instructed to rest their left middle, left index, right index, and right middle finger on the s, d, j, and k on the keyboard, separately representing for one color. They were told that a grey cross would always appear first in the center of the screen serving as a fixation point, and then one word written in different colors. The order is as follows: the fixation point appeared 600 ms, the word appeared 150 ms, then the empty screen appeared 2000 ms. Subjects were asked to identify the color in which the stimulus was written as fast and accurately as possible and responded by pressing the button of the corresponding color. The experiment was divided into a practice phase and a test phase. The practice phase was designed to rehearse the mapping of colors onto fingers and pressing of the response buttons. When the accurate rate reached 85%, the practice phase was ended. The formal test consisted of three blocks, and every block has 72 judge tasks (24 congruent stimuli, 24 neutral stimuli, 24 incongruent stimuli). They were instructed to avoid blinking and eye movement of any sort and to keep their eyes fixated on the monitor rather than looking down at their fingers during task performance. They can take a rest after finishing one block.

4.3. Electrophysiological recording and analysis

Brain electrical activity was recorded 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Product), with the reference on the left and right mastoids. The vertical electrooculogram (EOG) was recorded with electrodes placed above and below the left eye. All interelectrode impedance was maintained below 5 k Ω . The EEG and EOG were amplified using a 0.05–100 Hz bandpass and continuously sampled at 500 Hz/channel for off-line analysis.

Eye movement artifacts (blinks and eye movements) were rejected offline. Trials with EOG artifacts (mean EOG voltage exceeding $\pm 80 \mu\text{V}$) and those contaminated with artifacts due to amplifier clipping, bursts of electromyographic (EMG) activity, or peak-to-peak deflection exceeding 80 μV were excluded from averaging. The averaged epoch for ERP was 1000 ms including 800

ms poststimulus and 200 ms prestimulus. Of course, only segments with correct responses were averaged, and at least 40 trials were available for each subject, condition. On the basis of the ERPs grand averaged map and topographical map, the following 15 electrode points were chosen for statistical analysis: F3, Fz, F4, FC1, FCz, FC2, C3, Cz, C4, CP1, CPz, P3, Pz, P4. Inspection of the grand-average waveforms and the difference waves of incongruent minus congruent ERP indicated that there were two major effects of color–word interference: an early effect (350–550 ms) and a late effect (550–700 ms). The early effect was explored in 50 ms time windows from 350–550 ms. Mean amplitudes in each time window was analyzed using two-way repeated-measures analyses of variance (ANOVA). The ANOVA factors were task type (three level: congruent stimulus, incongruent stimulus, and neural stimulus) and electrode site. For all analyses, *P* value was corrected for deviations according to Greenhouse Geisser (Greenhouse and Geisser, 1959).

4.4. Dipole source analysis

Brain Electrical Source Analysis program (BESA, Version, 5.0, Software) was used to perform dipole source analysis. For dipole source analysis, the four-shell ellipsoidal head model was used. In order to focus on the scalp electrical activity related to the processing of the Stroop interference effect, the averaged ERPs evoked by the congruent stimuli were subtracted from the ERPs evoked by the incongruent stimuli. Principal component analysis (PCA) was employed in the interval from 450 to 500 ms in order to estimate the minimum number of dipoles. When the dipole points are determined, software will automatically determine the dipoles location. The relevant residual variance criterion was used.

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REFERENCES

- Ardi, R., Peter, H., 2002. Control of language use: cognitive modeling of the hemodynamics of Stroop task performance. *Cogn. Brain Res.* 15, 85–97.
- Atkinson, C.M., Drysdale, K.A., Fulham, W.R., 2003. Event-related potentials to Stroop and reverse Stroop stimuli. *Int. J. Psychophysiol.* 47, 1–21.
- Biederman, I., Tsao, Y.C., 1979. On processing Chinese ideographs and English words some implications from Stroop-test results. *Cogn. Psychol.* 11, 125–132.
- Bune, S.A., Hazelting, E., Scanion, M.D., 2002. Dissociable contributions of prefrontal and parietal cortices to response selection. *NeuroImage* 17, 1526–1571.
- Bush, G., Whalen, P.J., Rosen, B.R., Jenike, M.A., McInerney, S.C., Rauch, S.L., 1998. The counting Stroop: an interference task specialized for functional neuroimaging-validation study with functional MRI. *Hum. Brain Mapp.* 6, 270–282.
- Carter, C.S., Mintun, M., Cohen, J.D., 1995. Interference and facilitation effects during selective attention: an H215O PET study of Stroop task performance. *NeuroImage* 2, 264–272.
- Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D., 1998. Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science* 280, 747–749.
- Cohen, J.D., 1990. On the control of automatic processes: a parallel distributed processing model of the Stroop effect. *Psychol. Rev.* 97, 332–361.
- Donchin, E., Coles, M.G.H., 1988. Is the P300 component a manifestation of context updating? *Behav. Brain Sci.* 11, 355–372.
- Dong, R.G., Sun, X.R., Gao, S.R., 1996. Event-related potentials in reading Chinese characters—A preliminary study based on the shape-phoneme-meaning. *Clin. Neurosci. (China)* 4, 195–199.
- Dong, Y., Nakamura, K., Okada, T., Hanakawa, T., Fukuyama, H., Mazziotta, J.C., Shibasaki, H., 2005. Neural mechanisms underlying the processing of Chinese words: an fMRI study. *Neurosci. Res.* 52, 139–145.
- Greenhouse, W.W., Geisser, S., 1959. On methods in the analysis of profile data. *Psychometrika* 24, 95–112.
- Henik, A., 1996. Paying attention to the Stroop effect? *J. Int. Neuropsychol. Soc.* 2, 467–470.
- Ilan, A.B., Polich, J., 1999. P300 and response time from a manual Stroop task. *Clin. Neurophysiol.* 110, 367–373.
- Kern, J.G., Cohen, J.D., Stenger, V.A., Carter, C.S., 2004. Anterior cingulate conflict monitoring and adjustments in control. *Science* 303, 1023–1026.
- Kochunov, P., Fox, P., Lancaster, J., Tan, L.H., Amunts, K., Zilles, K., Mazziotta, J., Gao, J.H., 2003. Localized morphological brain differences between English-speaking Caucasians and Chinese-speaking Asians: new evidence of anatomical plasticity. *NeuroReport* 14, 961–964.
- Kutas, M., Hillyard, S.A., 1989. An electrophysiological probe of incidental semantic association. *J. Cogn. Neurosci.* 1, 387.
- Li, R.B., Peng, D.L., Guo, T.M., 2003. A study on Chinese and English semantic access with ERP technology. *Acta Psychol. Sin.* 35, 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.
- Logan, G.D., 1980. Attention and automaticity in Stroop and priming tasks: theory and data. *Cogn. Psychol.* 12, 523–553.
- Luo, Y.J., Wei, J.H., 1998. Review studies about the N400 of event-related potentials of Chinese and English language. *Adv. Psychol. Sci.* 6, 1–5.
- Macleod, C.M., 1991. Half a century of research on the Stroop effect: an integrative review. *Psychol. Bull.* 109, 163–203.
- Magiste, E., 1984. Stroop tasks and dichotic translation: the development of interference patterns in bilinguals. *J. Exp. Psychol., Learn Mem. Cogn.* 10, 304–315.
- Markela-Lerenc, J., Ille, N., Kaiser, S., Fiedler, P., Mundt, C., Weisbrod, M., 2004. Prefrontal-cingulate activation during executive control: which comes first? *Cogn. Brain Res.* 18, 278–287.
- McPherson, W.B., Holcomb, P.J., 1999. An electrophysiological investigation of semantic priming with picture of real objects. *Psychophysiology* 36, 53–65.
- Nakagome, K., Takazawa, S., 2001. Atopographical study of ERP correlate of semantic and syntactic violation in the Japanese language using the multichannel EEG system. *Psychophysiology* 38, 304–315.
- Peng, D.L., Guo, T.M., Wei, J.H., Xiao, L.H., 2004. An ERP study on processing stages of children's Stroop effect. *Sci. Technol. Eng.* 2, 84–88.
- Peterson, B.S., Skudlarski, P., Gatenby, J.C., Zhang, H., Anderson, A.W., Gore, J.C., 1999. An fMRI study of Stroop word–color interference: evidence for cingulate subregions subserving

- multiple distributed attentional systems. *Biol. Psychiatry* 45, 1237–1258.
- Plaut, D.C., McClelland, J.L., Seidenberg, M.S., Patterson, K., 1996. Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychol. Rev.* 103, 56–115.
- Posner, M.I., Snyder, C.R.R., 1975. Attention and cognitive control. In: Solso, R.L. (Ed.), *Information Processing and Cognition: The Loyola Symposium*. Erlbaum, Hillsdale, NJ, pp. 55–85.
- Qian, X.Y., Li, C., 2003. An introduction researches about neuropsychological evidence for the Stroop effect. *Psychol. Explor.* 3, 33–37.
- Rafal, R., Henik, A., 1994. The neurology of inhibition: integrating controlled and automatic processes. In: Dagenbach, D., Carr, T. H. (Eds.), *Inhibitory Processes in Attention, Memory, and Language*. Academic Press, San Diego, CA, pp. 1–52.
- Rebai, M., Bernard, C., Lannou, J., 1997. The Stroop's test evokes a negative brain potential, the N400. *Int. J. Neurosci.* 91, 85–94.
- Rowe, J.B., Toni, I., Josephs, O., 2000. The prefrontal cortex: response selection or maintenance within working memory? *Science* 288, 1656–1660.
- Stroop, J.R., 1935. Studies of interference in serial verbal reactions. *J. Exp. Psycho.* 18, 643–662.
- Sumiya, H., Healy, A., 2004. Phonology in the bilingual Stroop effect. *Mem. Cogn.* 32, 752–758.
- Tan, L.H., Liu, H.L., Perfetti, C.A., Spinks, J.A., Gao, J.H., 2001. The neural system underlying Chinese logograph reading. *NeuroImage* 13, 836–846.
- Tsao, Y.C., Wu, M.F., 1981. Feustal T. Stroop interference: hemispheric difference in Chinese speakers. *Brain Lang.* 13, 372–378.
- Van Orden, G.C., Johnston, J.C., Hale, B.L., 1988. Word identification in reading proceeds from spelling to sound to meaning. *J. Exp. Psychol., Learn Mem. Cogn.* 14, 371–386.
- Veen, V.V., Carter, C.S., 2002. The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiol. Behav.* 77, 477–482.
- West, R., 2003. Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia* 41, 1122–1135.
- West, R., Alain, C., 1999. Event-related neural activity associated with the Stroop task. *Cogn. Brain Res.* 8, 157–164.
- West, R., Alain, C., 2000. Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. *Psychophysiology* 37, 179–189.
- Zhou, X., Marslen-Wilson, W., 2000. The relative time course of semantic and phonological activation in reading Chinese. *J. Exp. Psychol., Learn Mem. Cogn.* 26, 1245–1265.
- Zhou, X., Marslen-Wilson, W., 1996. Direct visual access is the only way to access the Chinese mental lexicon. In: Cottrell, G.W. (Ed.), *Proceedings of the Eighteenth Annual Conference of the Cognitive Science Society*. Lawrence Erlbaum, New Jersey, pp. 714–719.