Right prefrontal laterality of Chinese boys during a Chinese high conflict Stroop task measured by multi-channel near-infrared spectroscopy imaging*

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Abstract Some studies have shown that native Chinese speakers have different laterality in matched Stroop tasks from native English speakers. Recently, many imaging data, which show left laterality of English-matched Stroop interference, have been reported. And a few functional imaging studies have been conducted to investigate the phenomenon of the Chinese version of Stroop task. In this study, functional activity in the lateral prefrontal cortex of a group of normal Chinese boys with functional near-infrared imaging during a Stroop color-word task was measured to show different Stroop interferences in the prefrontal cortex. The results show obvious fluctuation of the cerebral blood volume in the right prefrontal cortex in all boys, which agrees with the finding of previous studies, that is, Chinese native boys have right laterality in their brain when the Chinese version of Stroop color-word task is applied.

Keywords: laterality, Stroop effect, prefrontal cortex, near-infrared.

Stroop color-word interference refers to the phenomenon that the response times (RTs) of the color naming of a word depend on the congruence of the word color and the word meaning. Congruence refers to the relation of word color and word meaning: colored word matches the ink color in congruent stimuli (eg. word "red" printed in red ink), and colored word is different from the color ink in incongruent stimuli (eg. word "red" printed in blue ink). Generally, incongruent stimuli lead to greater interference than congruent stimuli. This also means that the RTs in incongruent stimuli are longer than that in congruent stimuli[1—4].

There are some differences between the processes of Chinese Stroop color-word trails for native Chinese speakers and the orthographic character tasks for other matched native language speakers, such as the English and the German[3]. The Chinese may be much more vulnerable to interference than other native language speakers[3,5]. Moreover, there is different hemispheric laterality of brain between them. A number of studies, supporting more interference in the left hemisphere during the trails of orthographic characters for matched language speakers, have been documented since laterality of Stroop effects was examined in the 1970s[3,5]. Furthermore, many of the neuroimaging studies, such as the functional magnetic resonance imaging[6—9], and the Positron emission tomography[8,10], have revealed a left-sided frontomedian and frontolateral network in English-matched Stroop tasks. On the contrary, right laterality has been shown in Chinese-matched Stroop tasks[11]. However, there are only a few published neuroimaging literatures to show the mechanism of Stroop effects for Chinese native speakers.

In our current experiment, we used Near-infrared imaging to study the Chinese Stroop color-word interference for Chinese speakers. Near-infrared imaging is a noninvasive method: sensitive, secure, cheap and repeatable[12,13]. Although it can only detect the region that is approximately 2 cm deep down in the brain tissues[14], it is still suitable to detect the prefrontal cortex (PFC) activity in Stroop tasks in children[15,16]. PFC is one of the most important functional regions in Stroop tasks, which is mainly related to the conflicting processing and the execution control[17]. The aim of the study is to assess the differences between the left- and the right-side of the

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prefrontal cortexes by imaging, so as to test the hypothesis of more interference in the right hemisphere of the brain during Stroop color-word trails in Chinese boys.

1 Materials and methods

1.1 Participants

A group of thirty-four boys with a mean age of 14.6 (standard deviation $SD = 3.4$) years old and from regular education classes with normal intelligence quotient (range: 93—125) is included in the study. All participants are native Chinese, and right-handed according to the classification standard of Chinese handedness[18]. They have no neurological, psychiatric disorder or associated history. The guardians of all participants have given written consent in accordance with the institutional guidelines.

1.2 Psychological process

The paradigm used in this study is a Chinese Version of Stroop color-word task revised from Kern's study[19]. In the task sequence, 80 trials, made up of 56 congruent trials (70%) and 24 incongruent trials (30%), were arrayed proportionally and pseudo-randomly. Less incongruent trails were used in order to get higher conflict and interference of incongruent trails, since more incongruent trails could lead to more behavior adjustments required for execution of incongruent trials and accordingly reduce the conflict and interference. The trials were 3 s long and consisted of a stimulus of 1.5 s followed by a fixation cross (+) of 1.5 s. The stimuli comprise of either one of the three Chinese characters (red, green or blue) printed in one of the three colors on a black background. In addition, four congruent trials were added before and after the 80 trials respectively to increase the conflict effects of incongruent trails. The participants were instructed to name the color of the stimulus, ignoring the Chinese character. Then, they were required to press the corresponding button provided as soon as they identified the color ink. The paradigm in this study was coded by cogent2000[20] which ran in Matlab (version 6.5, release 13).

1.3 Acquisition of near-infrared functional images

A multi-channel near-infrared spectroscopy imaging system1) was used to detect the functional changes of PFC. The main substances in human tissue such as water and hemoglobin can absorb less near-infrared light of wavelength from 700 to 900 nm. This is because lights within such wavelength range can penetrate through the human tissue better. Since the oxy- and the deoxy-hemoglobin have the same absorption coefficient at 808 nm, we chose light of 808 nm as the light source. Therefore, the data obtained from the experiment would not be affected by the oxygen saturation in the blood. Furthermore, the hemoglobin can absorb greater light of such wavelength than the water. Hence, in the current experiment, the main absorbing substance for 808 nm light was hemoglobin.

A probe of 10 cm × 6 cm, with the detectable depth of 2 cm, which could be used to detect the activity of the prefrontal cortex of a child, was used in this study. Near-infrared images were reconstructed by spatial location weighted optimization scheme[21]. The signal of a pixel was a non-dimensional value and was directly proportional to the changes of the quantity of light-absorbed substance. The intensity of the images could be nearly proportional to the changes of the cerebral blood volume (CBV) relative to the rest baseline, and the positive and negative signals indicated the increases and decreases of CBV, respectively.

The detector was placed on each of the participant's forehead with its low edge and middle line superposed with the superciliary arch and sagittal to the middle line respectively. Thus, the detected area was roughly within the region of Fp1, F3, F4 and Fp2 in the international 10—20 system (Fig.1).

In this experiment, the participant was seated on an electroencephalography chair in a dim-lighted room. The near-infrared detection was synchronized with the psychological task, and a set of data of roughly 24 frames was acquired at the speed of one frame in every 10 seconds. Before the behavior process, the basic data for reconstruction were acquired during the rest mode of the boys with both eyes closed.

1.4 Data analysis

The images were partitioned into four sections for analysis: upper-left, lower-left, upper-right and lower-right. The median and standard deviations of

1) Bai J, Zhang Y and Xu C. Chinese Patent, 200410096077.X (*proclaimed*).

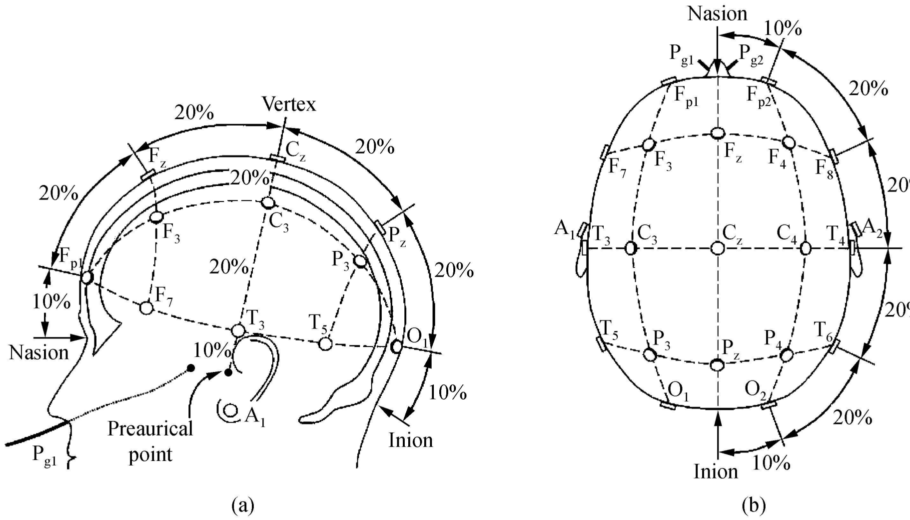

Fig. 1. The international 10—20 system seen from (a) left and (b) above the head. A= Ear lobe; C= central; Pg= nasopharyngeal; P = parietal; F=frontal; Fp= frontal polar; O= occipital.

near-infrared images time series were calculated and analyzed statistically. For the unknown distribution of the signal, Wilcoxon test was used for the significance test among the four regions.

In consideration of the random effects of individual diversity, the linear mixed models were applied to analyze the behavior data of the response time. The fixed and random effects were estimated by the restricted maximum likelihood (REML) algorithm, and analysis of variance (ANOVA) was used to infer statistical significance of inter-stimuli-kind variance components of fixed effects. Image processing and statistical analysis were done in R environment (Version 2.4.0)[22].

2 Results

2.1 Behavior results

The mean accuracy rate of all trails was 96.1% (SD=2.5%), and the accuracy rates of incongruent and congruent trails were 94.6% (SD=4.7%) and 96.8% (SD=2.6%), respectively. There were no statistically significant differences on the confidence of 0.01 between the two kinds of stimuli (t-test, $p=0.0164$).

With the error responses eliminated, the analysis of the response time showed significant Stroop effects. The mean RTs of the congruent and incongruent stimuli were 672.8 ms (SD=124.2 ms) and 741 ms (SD=84.0 ms), respectively. The difference of RTs between congruent and incongruent stimuli for each boy was significant (t-test, $p<0.01$). Based on the linear mixed models with the fixed effects of different stimuli and the random effects of participants, the hypothesis test showed that the Stroop effects were significant: the RTs to the incongruent trails were significantly longer than that to the congruent trails ($F_{(1, 2580)}=197.17$, $p<0.0001$).

2.2 Near-infrared imaging results

The medians along the time series were calculated and the numbers of pixels within the four regions were counted. As shown in Table 1, the number of pixels within the four regions during the task has no significant differences when compared to each other on the confidence of 0.01 by using the paired Wilcoxcon test. However, the number of pixels with positive median in the upper-right region was larger than the other three regions, whereas the number of pixels with negative median was smaller. The numbers of subjects holding positive averaged median in the upper-left, lower-left, upper-right and lower-right regions were 14, 18, 23 and 12, respectively. Furthermore, the upper-right region held larger average median of time series (Table 1), which indicates higher CBV in the upper-right cortex during the task, despite that Wilcoxcon test with confidence of 0.01 showed no significant differences when compared to each other.

Table 1. The parameters of CBV in four regions

Position	The number of pixels		Averaged median of time series[2)]	Averaged standard deviation[3)]
	Positive median[1)]	Negative median[1)]		
Left-upper	131.1±137.1	130.5±137.6	−0.000725±0.185	0.191±0.241
Left-down	174.1±133.7	144.5±124.6	0.0107±0.145	0.0956±0.156
Right-upper	196.8±191.4	90.0±139.2	0.0930±0.409	0.365±0.286
Right-down	132.6±80.1	168.3±97.3	−0.0511±0.302	0.169±0.256

1) Positive and negative median of time series of every pixel were tested by Wilcoxcon test on the confidence of 0.01.
2) Values for each subject was calculated by averaging the medians in time series of the corresponding regions.
3) Values for each subject was calculated by averaging the standard deviations in time series of the corresponding regions.

When the time series of the four regions were compared, the signal from the upper-right region is much more fluctuant (Fig. 2). The mean of standard deviation of time series of every pixel in the upper-right region was significantly larger than that in the other regions when using the paired Wilcoxcon test ($p<0.001$). The lower-left region had the smallest standard deviation of time series tested by respective Wilcoxcon test ($p<0.001$). The difference between the lower-left and upper-right regions showed no statistical significance (paired Wilcoxcon test, $p=0.043$).

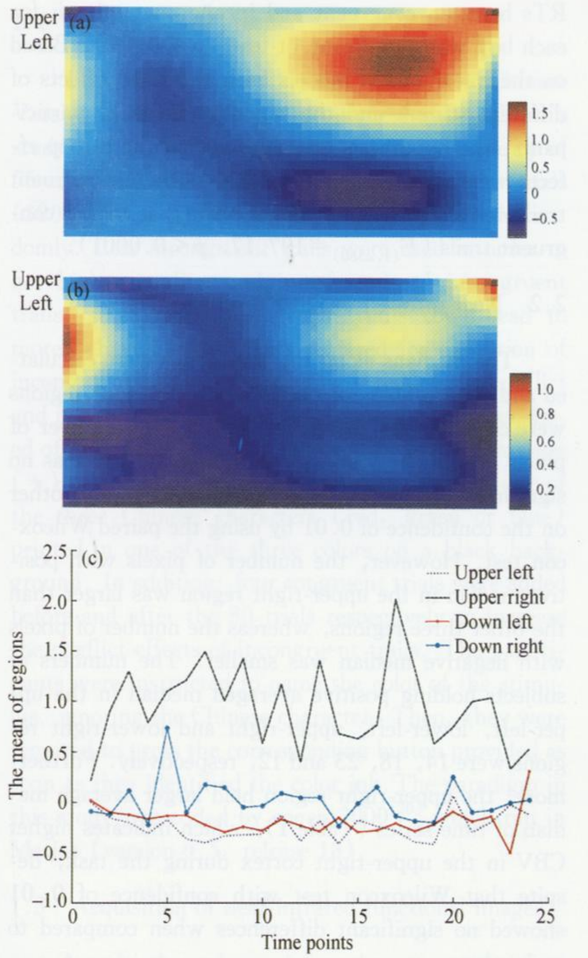

Fig. 2. The signal properties of the four prefrontal regions. (a) The median image during the task, showing high median in the right upper region; (b) the standard deviation image during the task, showing large standard deviation in the right upper region; (c) the changes of the median in time series.

3 Discussion and conclusion

As we were more interested in the interferential effects rather than the differences between incongruent and congruent trials (the differences between incongruent and congruent could not be differentiated in the current study), we chose the fast event-related task combined with the near-infrared imaging system with relatively low scan speed, instead of a slow event-related task or a block task.

The main findings of the present investigation are: a) the signal in the upper-right region of the prefrontal cortex fluctuated much severely, which also means that the CBV of the region shows stronger fluctuation; b) the increased CBV of the upper-right region during the task is also the largest, although no statistical significance was shown in the differences between the two regions. The findings imply that the left- and right-PFC have different functional states in the condition of significant Stroop interference. We assume that the asymmetric CBV changes result from asymmetric Stroop interference in the brain: the stronger fluctuation of CBV in the right cortex means greater interference on the right cortex according to the laterality of Stroop inference[3]. The right laterality of Chinese-matched Stroop effects was first shown by Tsao et al.[11], who compared in a language-matched Stroop task for Chinese adult speakers the interference intensity under two circumstances, when the Stroop stimuli were displayed solely in the left visual field and the stimuli were displayed only in the right hemisphere of the brain. However, a number of psychological literatures regarding English- or German-matched Stroop tasks have drawn the conclusion that the left hemisphere of the brain generally shows more interference than the right hemisphere[3]: different language-matched Stroop interference results in different hemispheric interference in the brain. Moreover, a left-sided frontomedian and frontolateral network for Stroop tasks has been revealed in many recent neuroimaging studies[6—10]. Different mechanism of words processing may explain the phenomenon. Stroop interference is a result from which the process of color naming is disturbed by the process of words: a proficient speaker cannot withhold accessing word meaning in spite of explicit instructions to attend only to the Page 9 color in which the words are printed[23,24]. English words may be intergraded by phonetic effects between graphics and word characters[25], and these effects are processed in the left hemisphere of the brain of a native English speaker[11]. However, the processing of the Chinese color characters might be directly from graphical forms to word meanings or through less phonological effect to word meanings[26], and Chinese color characters and color information may be competing for shared right-hemisphere perceptual capacities in the right-handed Chinese-speaking subjects[11]. Hence, in the right hemisphere of the brain, the predominant hemisphere of Chinese logographs, color naming is interfered more strongly in Chinese-match Stroop tasks by Chinese-words process. With this, the right hemisphere of the brain should work more than the left hemisphere in order to overcome the interference. As for the English-matched Stroop experiments, it is the left hemisphere of the brain that needs to work harder to execute the tasks.

Indeed, it is shown in the neuroimaging studies that other areas beside PFC, such as the dorsal prefrontal cortex, anterior cingulated cortex, parietal cortex and parieto-occipital cortex, were involved in coping with Stroop interference[19]. Although many studies have stated that the dorsal lateral prefrontal cortex (DLPFC) and anterior cingulated cortex (ACC) are more important in the neural mechanism of Stroop interference, these areas are beyond our probe area due to the limited depth penetration of near-infrared and the limited size of the detector. However, the significant changes of CBV in the prefrontal cortex were obtained in the current study, which has not been found yet in any fMRI studies. In fact, similar data were also reported by Schroeter et al., who has observed visible changes in the CBV at F3 and F4 of international 10—20 system during Stroop tasks[13]. In their data, the change of oxygen saturation was less in F3 and F4 than in DLPFC. This is possibly the reason why blood-level dependent fMRI, which is only sensitive to oxygen saturation, could not show the functional activation in the sections detected in the current study.

In summary, our study is the first functional multi-channel near-infrared spectroscopy imaging study on the evaluation of Chinese-matched Stroop interference. We utilize near-infrared images to record CBV changes of prefrontal cerebral cortex in a group of normal Chinese boys during the Stroop task. With the help of the newly introduced technique, our study shows that native Chinese boys hold right hemispheric laterality of Chinese-matched Stroop interference in their brains. A multi-channel near-infrared spectroscopy imaging system can detect the changes of blood flow in certain regions of the brain, whereas single- and dual-channel near-infrared system can only measure the blood flow at one or two points of the brain. Thus, the measured areas are expanded by using the multi-channel near-infrared spectroscopy imaging system, and the reliabilities are enhanced. However, there are still some disadvantages of the current imaging system, including: a) the limited penetration depth of near-infrared light constrains further application of the near-infrared imaging system in detecting any of the deep functional structures; b) the images cannot synchronize with the changes of the brain activities in response to the different stimuli because of the lower time resolution in our study. Furthermore, multi-channel near-infrared spectroscopy imaging is a relatively new functional imaging. Therefore, more studies would be required to test its validation, especially when compared with other functional imaging methods.

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