Reduced prefrontal cortex activation in the color-word Stroop task for Chinese dyslexic children: a near-infrared spectroscopy study

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Abstract. Behavioral studies have investigated the performance of children with developmental dyslexia in conflict resolution, a function connected with the prefrontal cortex (PFC) closely. However, little is known about the prefrontal activation in conflict resolution for dyslexic children. In the present study, the involvement of the PFC in resolving conflict was evaluated for Chinese dyslexic children by means of near-infrared spectroscopy (NIRS). The NIRS instrument is a portable, continuous-wave system and can measure concentration changes of hemodynamic parameters (including oxy-, deoxy-, and total hemoglobin). Considering better sensitivity, the oxy-hemoglobin (oxy-Hb) was chosen to indicate the prefrontal activation. Ten dyslexic children and 11 normal children were recruited to perform the Chinese-character color-word Stroop task, which included the neutral and color (incongruent) tasks. In behavioral performance, both groups showed significant Stroop effect, longer response time or higher error rate for the color task. In particular, the Stroop interference effect was marginally larger for dyslexic children than normal children in response time. What’s more, the two groups showed distinct pattern of oxy-Hb activation during the Stroop tasks. The normal group recruited the bilateral PFC to perform the tasks, while the dyslexic group couldn’t activate the bilateral PFC in the difficult color task. Moreover, significantly less color Stroop effect was found in the left PFC for the dyslexic group, showing their disability in coping with the Stroop interference. These findings suggest that the PFC is dysfunctional in conflict resolution for Chinese dyslexic children and that NIRS can be an effective tool in neurological research and clinical application.

Keywords: Developmental dyslexia, Chinese, Conflict resolution, Stroop, Near-infrared spectroscopy

1. Introduction
Developmental dyslexia (DD) is defined as a disorder represented by unexpected reading disabilities in people who otherwise have the normal intelligence and education [1, 2]. Affecting approximately 5-17% of the school-age children, DD is one of the most common problems, and is characterized by difficulties with accurate and fluent word recognition, spelling and decoding. Although DD has been viewed as a specific phonological deficit [3], more and more evidence has pointed out that people with DD also show deficits in other domains which have been demonstrated to contribute to the reading performance for the dyslexic children [4], such as attention [5], visual processing [6] and executive function [4, 7].

In the executive function domain, although an increasing number of behavioral studies have reported defective performance for dyslexic children in certain functions, such as working memory [7, 8], verbal fluency function [4, 7, 8] and conflict resolution [7, 8], little is known about the neural correlates of executive function in dyslexic children.

Conflict resolution is one major role of executive function, and is critical in keeping adequate performance in the complex situation with significant interference between two or more sources of information. Functional neuroimaging studies have confirmed that the PFC, especially the dorsolateral PFC, is involved in resolving conflict [9, 10]. The PFC reallocates and maintains the attention on the task-relevant stimulus dimensions and processes, while inhibits the task-irrelevant information and responses. The Stroop paradigm is a classical method to study the conflict resolution mechanisms, introduced by John Ridley Stroop in 1935 [11]. The main feature of the Stroop paradigm is selecting to respond to a certain dimension of the stimulus over other dimensions. In the color-word Stroop task, the subject is usually instructed to respond to the color of the stimulus while ignoring to read the word. Since reading the word is a more prepotent response than naming the color, lexical and hue conflict with each other when the presented color of the stimulus is incongruent with its meaning. In addition, the color-word Stroop task has been widely used to investigate the abnormal brain function of conflict resolution in many neurological and psychiatric disorders [12].

Near-infrared spectroscopy (NIRS) is a noninvasive optical functional neuroimaging method. Due to the sensitivity to the oxygenation state of hemoglobin, NIRS can measure concentration changes of oxy-hemoglobin ($\Delta$[oxy-Hb]), deoxy-hemoglobin ($\Delta$[deoxy-Hb]) and tot-hemoglobin ($\Delta$[tot-Hb]), which have been proved to reflect the cortical activation in the activated areas by simultaneous measurement with other imaging methods [13, 14]. Compared with functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), NIRS has advantages in its insensitivity to movements and flexibility. In particular, low susceptibility to movement artifacts makes it available to measure in natural conditions and more suitable in children studies [15] and psychiatric and neurological research, such as depression [16], schizophrenia [16, 17], panic disorder [18], attention-deficit hyperactivity disorder [19], and pervasive developmental disorder [20]. Although with a limited penetration depth by NIRS, an appropriate separation between the source and the detector allows the measurement of hemodynamic activation from the cerebral cortex [13]. What’s more, NIRS has been used to measure the brain activation in the PFC during the Stroop task [10, 21].

In this study, we aim to evaluate the PFC function in conflict resolution for Chinese dyslexic children. NIRS was used to measure the activation of the PFC while participants were performing the Chinese-character color-word Stroop task, consisting of the neutral and color (incongruent) tasks. We expected to observe lower prefrontal activation during the Stroop task for dyslexic children than normal children.

2. Experimental Procedure

2.1. Subjects
Twenty-one Chinese primary school children, grades 4 to 6, participated in this study: 10 dyslexic children (3 girls and 7 boys, age 10-13 years old) and 11 age-matched normal children (1 girl and 10 boys, age 9-12 years old). All participants were right-handed, had normal or corrected-to-normal vision and normal color vision, and were healthy without personal or family history of neurological
disorders. According to the definition of dyslexia by International Classification of Diseases 10 (ICD-10), children meeting the following criteria were defined to be dyslexic: (1) the score for Pupil Rating Scale Revised Screening for Learning Disabilities (PRS) was equal or less than 65, implying the possibility of learning disability; (2) the score of the Dyslexia Checklist for Chinese Children (DCCC) was equal or greater than 70, suggesting that their reading achievement was two standard deviations or more below the average level; (3) the Chinese achievement fell in the last 10 per cent in the class; (4) the intelligence quotient (IQ) was above 80 evaluated with Wechsler Intelligence Scale for children-Chinese revision (WISC-CR) [22]. The normal children didn’t have the PRS, DCCC and IQ tests and were chosen primarily on their Chinese achievement and their teachers’ recommendation. The two groups didn’t differ in age, education and IQ (p>0.34).

After complete depiction about the experiment, informed consent was collected from each subject and their parents before the experiment. This study was approved by the Human Subjects Institutional Review Board at Huazhong University of Science and Technology.

2.2. Stimuli and procedure

The Chinese-character color-word Stroop experiment consisted of two kinds of stimuli: neutral (color-irrelevant) characters (穿, 奖, 球, 涂, mean “pass through”, “prize”, “ball”, and “scrawl”), and color characters (红, 黄, 蓝, 绿, mean “red”, “yellow”, “blue”, and “green”). Each character was presented in four colors: red, yellow, blue and green. To reflect the conflict, color characters showed only in the incongruent color were chosen as stimuli. The subjects were instructed to judge the color of the stimulus while ignoring its other dimensions as fast and accurately as possible. If the character was printed in “red”, subjects press the D button with the middle finger of the left hand; if in “yellow”, they press the F button with the index finger of the left hand; if in “blue”, they press the J button with the index finger of the right hand; if in “green”, they press the K button with the middle finger of the right hand.

The experiment was conducted in block design [23] and in a single run (figure 1), including two rest blocks, a white cross showing in the centre of the screen for 1 min, and two task blocks, neutral task and color task for neutral and color stimuli respectively. In each task block, 40 stimulus trials were included and were in a pseudorandom order. In each trial, an empty screen remained for 2 s, followed by a stimulus showing for 1 s. The total time of the experiment was 6 min. The order of the task blocks were counterbalanced across subjects. Before the formal experiment, there was a practice block to ensure the subject to understand the task instructions.

![Figure 1. Experimental design of the Stroop task.](image)

2.3. NIRS

A portable, continuous wave NIRS imager with a sampling rate of 3.3 Hz was utilized to detect the concentration changes of oxy-, deoxy-, and tot-hemoglobin. The imager consists of a personal computer, a measuring and controlling module and a probe [24]. The probe includes 4 sources and 8 detectors defining 16 measured areas represented by channels and it covered almost the whole forehead of the subject during the entire experiment, as shown in figure 2. The distance between the source and the detector is 2.45 cm approximately, which allows the measurement of hemodynamic activation from the cerebral cortex [13]. Since △[oxy-Hb] has been proved to be more sensitive
compared with the other two hemodynamic parameters [15, 25], it was chosen as the indicator of the task activation in this study.

The raw data collected by the NIRS imager were first processed to remove the noise caused by movements, then converted to concentration changes of hemodynamic parameters according to the modified Beer-Lambert Law, and finally bandpass filtered to remove the slow baseline drifts and other physiological noise. The mean signal intensity was calculated for the baseline (30 s before the task) and the vascular response (entire period of the task) for each task and each subject. Difference of the signal intensity between the baseline and the vascular response was taken as the task activation and the task activation was compared against 0 with paired t tests to determine the channels with significant activation for the two tasks. Independent t tests were used to analyze the group differences. The results reached significant level if p<0.05.

![Figure 2. Location of the NIRS probe and the 16 measured areas represented by channels. “#” denotes channel.](image)

3. Results

3.1. Behavioral data

The behavioral results are displayed in figure 3. Concerning the response time, a repeated measure task (neutral, color) × group (normal, dyslexic) analysis of variance (ANOVA) revealed a significant main effect for task (F(1,19)=13.946, P=0.001) and marginally significant task × group interaction (F(1,19)=4.13, P=0.056), whereas there were no main effect for group. The response time was evidently longer for the color task than the neutral task in both groups (normal: t=2.323, p=0.043; dyslexic: t=4.136, p=0.003; paired t test). In particular, there was a statistical trend towards a larger Stroop interference effect in dyslexic group (t=2.032, p=0.056). For error rate, the repeated ANOVA demonstrated a significant main effect for task (F(1,19)=11.347, P=0.003), without the main effect of group or an interaction. The error rate of the color task was significantly higher than that of the neutral task for the dyslexic group (t=2.61, p=0.028, paired t test), but not for the normal group. Although the dyslexic group had more errors, they did not differ from the normal group in error rate for the two tasks or the Stroop effect significantly.

![Figure 3. The response time and error rate of the neutral and color tasks for the two groups. N for the normal group, and D for the dyslexic group. Mean ± SEM (standard error of measurement).](image)

3.2. NIRS data

For the neutral task, the paired t tests demonstrated evident oxy-Hb increase in three channels (channels 1, 2, 15) for the normal group, and in four channels (channels 1, 3, 5 14) for the dyslexic
group. No statistically significant difference between groups was found. For the color task, the normal group activated nearly all the channels (except for channel 14), while the dyslexic group couldn’t effectively activate any channel. What’s more, independent t tests revealed that the normal group showed larger oxy-Hb activation in channel 3 ($t=2.601$, $p=0.018$, Cohen’d=1.14), channel 7 ($t=2.23$, $p=0.038$, Cohen’d=0.97) and channel 11 ($t=2.177$, $p=0.042$, Cohen’d=0.95) than that of the dyslexic group.

With regard to the color Stroop interference effect, activation difference between the color task and neutral task, it was significant in channel 5 ($t=2.319$, $p=0.043$) and channel 6 ($t=2.627$, $p=0.025$) for the normal group, whereas it was not evident in any channel for the dyslexic group. Comparison between groups showed greater color Stroop interference effect in channel 5 ($t=2.273$, $p=0.035$, Cohen’d=0.92) and channel 7 ($t=2.199$, $p=0.04$, Cohen’d=0.9) for the normal group than dyslexic group (figure 4).

4. Discussion

In the present study, NIRS was utilized to evaluate the PFC activation in conflict resolution during the Stroop task for Chinese dyslexic children. In behavior, there was a statistical trend towards a larger Stroop interference effect for dyslexic group, though without significant difference in response time or error rate. The result consists with previous studies showing that the Stroop interference is negatively associated with reading abilities [26, 27]. The larger Stroop interference suggested the poor cognitive control for dyslexic children. In addition, NIRS data revealed distinct brain activation pattern for the two groups, the reduced prefrontal activation showing the dysfunction of the PFC in conflict resolution for dyslexic children and conforming to our initial assumption.

The normal children recruited the bilateral PFC to perform the Stroop task, and the activation level increased and the activation field enlarged from the neutral to the color task. Further, when comparing the color task with the neutral task, only activation in the left PFC (Channels 5, 6) reserved, which proved the involvement of the left PFC in conflict resolution for children. The results are concordant with the well-established notion that the dorsolateral PFC plays a top-down role in the conflict resolution by maintaining the attention demands on the current task while suppressing the distracting information [9, 28, 29]. Our finding is also well in line with the recent functional imaging studies on children in different kinds of conflict tasks. Schroeter et al. used a Stroop paradigm with event-related fMRI and reported that children utilized the left lateral PFC to copy with the Stroop-related interference [30]. Another study by Konrad and colleagues, using the flanker task, found that children activated the left middle frontal gyrus (MFG) in executive control of the conflict [31]. What’s more, our results concur with some studies on adults [9, 10].

Compared with the controls, the PFC was not significantly activated in the color task for dyslexic children. What’s more, there was a significantly smaller color Stroop effect in the left PFC (Channels
5, 7) for the dyslexic children. The decreased activation in the PFC suggested that this area couldn’t be recruited in conflict resolution for the dyslexic group, which might contribute to their larger Stroop interference in behavior. The weaker activation in the PFC was also reported in other cognitive task, such as working memory task, for dyslexic children [32]. Siok et al. have reported reduced gray matter volume in the MFG for Chinese dyslexic children [33] and it might be possible that the structural abnormality caused the PFC dysfunction and made it less sensitive to the increasing attention demands and task difficulty and more active in undemanding task.

There were some limitations in the present study. Firstly, the NIRS probe used in this study covered just part of the PFC. Hence the involvement of other brain regions in conflict resolution could not be assessed, such as posterior parietal cortex. Further studies measuring more brain regions can demonstrate this issue more comprehensive. Secondly, the sample size was small. However, it should be pointed out that the activation difference between groups was significant with large effect size.

Taken together, NIRS can effectively measure reduced prefrontal activation during the Stroop task for Chinese dyslexic children, suggesting the PFC dysfunction in conflict resolution for dyslexic children. This study contributes to our knowledge about the neural correlates of executive function in DD, and suggests that the executive function should be considered in the diagnosis and treatment of the dyslexia. Our findings elucidate that NIRS can be an effective tool in neurological research and clinical application.

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