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Using fNIRS to study the brain activation and networks associated with Chinese character recognition

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Abstract. In this study, functional near-infrared spectroscopy (fNIRS) was used to examine the brain activation patterns in the occipitotemporal cortex (OTC) associated with Chinese character recognition (CCR). Eighteen healthy participants were recruited to perform a well-designed task involving three types of stimuli including real characters, pseudo characters and checkerboards. By inspecting the brain activation difference and its relationship with behavioral data, we discovered that the left hemisphere is responsible for the orthographical information processing. Meanwhile, we found that the bilateral superior temporal gyrus (STG), bilateral Brodmann's area (BA) 19 and left fusiform gyrus were involved in high-level lexical information processing such as semantic and phonological ones, indicating that the brain activities in these regions were associated with enhanced CCR performance. In addition, by examining functional brain networks, it was discovered that increased brain connectivity in the right BA 19 exhibited significant correlation with the performance of CCR. Consequently, the combination of fNIRS technique with functional network analysis paves a new avenue for an improved understanding the cognitive mechanism underlying CCR.

Key words: Chinese character recognition; fNIRS; visual word form; brain connectivity

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1 Introduction

The word/character recognition is characterized by the process of three cognitive components: orthographic processing, semantic processing, and phonological processing. Interestingly, the Chinese writing system is different from English and other alphabetic ones, in which the radicals in Chinese characters are combined in a two-dimensional configuration while alphabetic words consist of only the one-dimensional linear combination of letters. To date, various models have been developed to address the complex mechanism underlying Chinese character recognition (CCR) or word recognition in alphabetic languages such as English.

In this study, fNIRS[1-8] was used to examine the brain connectivity and activation in occipitotemporal cortex (OTC) during CCR. It is hypothesized that brain activation patterns and brain networks should exhibit significant differences between the non-orthography processing, orthography processing and high-level lexical information processing such as the phonological and semantic information processing. To test the hypothesis, the visual lexical decision paradigm, which is widely used for exploring the cognitive process of word/character recognition[9] is adopted for the present work. The visual lexical decision task consists of three types of stimuli: checkerboards, pseudo characters, and real characters. According to the lexical constituency model[10], checkerboards contain no orthographic information, pseudo characters involve processing orthographic information without touching upon phonological and semantic information, whereas real characters implicate orthographic, phonological, and semantic information. In addition, we compared and inspected the differences in the brain functional activation and connectivity between the orthography and checkerboard cases, and those between the real character and pseudo character cases. Further, we correlated the differences in brain activation and connectivity between the real character and pseudo character cases with their differences in accuracy and reaction time. The differences represented the discrimination to the pseudo characters based on subjects' Chinese character recognition ability, which measured the CCR ability in a more comprehensive way. It is expected that the investigation into the brain connectivity and activation during CCR by using fNIRS will help establish a new method for improving the understanding of neural mechanism of CCR in a comprehensive way.

2 Methods

2.1 Participants

Eighteen subjects (10 females, eight males) participated in this study. The age range was from 20 to 32 years (mean age: 25.3 years). All participants were college students, who were right-handed, native Chinese mandarin speakers, and had normal or corrected-to-normal vision. All subjects were required to sign informed consent documents prior to the experiment. This study was approved by the Medical Ethics Committee with the University of Macau.

2.2 Task and Materials

This study included three types of stimuli: (1) Chinese characters (real characters); (2) pseudo characters; and (3) non-character checkerboards. Each of the three categories of stimuli consisted of 48 different items, and all the 144 items were presented randomly. Real characters adopted in the study were commonly used ones with the highest frequency (mean frequency: 450.94 per million words). The frequencies of real characters were calculated according to a database based on film subtitles. By contrast, pseudo characters were artificially produced by using combined radicals from real characters. More importantly, the components of pseudo characters were placed in appropriate configurations, following the same orthographic rules as real characters. The only difference between the pseudo and real characters was that pseudo ones were meaningless and unpronounceable, in which pseudo characters were orthographically legal without having lexical representation. The stimulus set of checkerboards was neither orthographically legal nor of lexical representation.

2.3 Procedure

Participants were seated comfortably in a quiet room with about 70 cm away from the computer monitor. Visual lexical decision tasks were performed for the present study, in which participants were instructed to determine whether a stimulus was a Chinese character or not, by pressing specific keys with their left or right forefinger. The response hands were counterbalanced across participants. After a brief practice, participants were requested to perform the visual lexical decision task with three runs. Each run included 48 event-related trials and the duration of each trial was 15.5 s, which included a pre-stimulus period of 500 ms with a black fixation cross presented in the center of the monitor, a stimulus period of 2000 ms with the first 1000 ms severed as the response window, and then a post-stimulus and recovery period of 13 s with a red fixation cross displayed in the center of the monitor (**Fig. 1**). It took about 40 minutes to finish the experiment. Participants were allowed to have a short break between different runs, the duration of which could be determined by each individual subject.

2.4 fNIRS Data Acquisition and Preprocessing

A continuous wave (CW) fNIRS system (CW6 fNIRS system; TechEn Inc., Milford, MA) was used to measure the concentration changes of HbO and HbR. This system had four laser sources at wavelengths of 690 nm and 830 nm and eight optical detectors. The optodes were positioned on each participant's head with two home-made plastic patches (4.24 cm × 8.49 cm), which can cover the occipitotemporal gyrus (**Fig. 2**). The configuration of the source and detector pairs can generate 12 channels, and the inter-optodes distance was 3cm. A three-dimensional (3D) digitizer (PATRIOT, Polhemus, Colchester, Vermont, USA) was used to measure the 3D coordinates of the optodes. The average 3D coordinates were further imported to NIRS_SPM software for spatial registration, which can generate the distributions of the optodes and channels (**Fig. 3**) and3D MNI coordinates of each channel. The sampling rate of this system is 50Hz. fNIRS signals were processed by using HomER2 software[11].

2.5. Network Construction and Analysis

The nodes and edges are the two essential components to construct the brain networks. In this study, the node is denoted as the channel while the edge is defined as the Pearson correlation coefficient calculated from measurements between two channels. All correlation coefficients were then transformed into *z*-scores with the Fisher transformation. All the *z*-scores were then averaged across participants for each condition, which were converted back to correlation coefficients again.

To construct the brain network, the correction coefficients were binarized by setting a threshold *T*. The nodal degree was compute to measure the importance of a node in the brain network . The nodal degree means the number of edges directly linked to a node. Since there is currently no unified standard for threshold selection (Zhang et al. 2016), this study take the whole correlation coefficient range of $0 < r < 1$ (interval = 0.01) as the threshold. The correlation coefficients higher than a series of thresholds were visualized in binary maps for each condition.

2.7. Statistical Analysis

For behavioral data, the accuracy and reaction time were subjected to a 3 × 1 repeated measures analysis of variance (ANOVA), respectively, with stimuli type as a within-subject factor. Post-hoc tests were performed with Sidak adjustment.

The HbO concentration difference and nodal degree difference between the orthographically legal stimuli and checkerboards cases, and the difference between the pseudo and real character cases during high-level lexical information processing were then carefully examined. Two-tailed paired *t*-tests were performed on the mean z-scores for each channel.

Further, we correlated the differences in HbO concentration and nodal degree between the real character and pseudo character cases with their differences in accuracy and reaction time. The significance of the correlation was also examined.

3 Results

3.1. Behavioral results

The repeated one way ANOVA were conducted between the three conditions for all behavior data. We discovered that the stimuli type showed significant effect on reaction time and accuracy, $p < 0.01$. The behavioral data also exhibited significant difference between each of the two conditions, $p < 0.01$ (**Fig. 4**).

3.2. Brain activation

The time courses of mean HbO signals (z-scores) were depicted in **Figs. 5 and 6**. The *t*-values, resulted from two contrasts (the HbO signals difference between the orthographically legal stimuli and checkerboards cases, and the difference between the pseudo and real character cases), were visualized on a brain cortex template as illustrated in **Fig. 7**.

A clear left laterality was observed in the *t*-map when comparing the findings between the orthography and checkerboard cases, especially for the left BA 19 (channel 12, $t(17) = 1.21$, $p = 0.24$, Cohen's $d = 0.21$), although the tendency was not that significant. In addition, the checkerboard case showed enhanced activation in the right STG (channel 2, $t(17) = -2.59$, $p = 0.02$, Cohen's $d = -0.40$) and right BA 19 (channel 5, $t(17) = -2.81$, $p = 0.01$, Cohen's $d = -0.42$).

3.3. Brain network analysis

The binary maps were generated with the thresholds ranged from 0.86 to 0.95. **Fig. 8** visualized the connectivity above the threshold of 0.95, in which the orthography condition case exhibited increased functional connectivity in the right BA 19 (channel 3). The binary maps implied that the right BA 19 (channel 3) played a key role in the perception of orthography stimuli.

Consistent with the findings revealed by binary maps, we discovered an increased nodal degree in the right BA 19 (channel 3) in orthography condition ($t(17) = 2.46$, $p = 0.02$, Cohen's $d = 0.34$).

4 Discussion

To the best of our knowledge, this is the first study to explore the role of OTC in CCR by using fNIRS. In particular, the present study examined the brain activation patterns and functional brain connectivity during orthographic processing, and high-level lexical information processing such as phonological and semantic processing.

By using fNIRS, we successfully differentiated the brain activation pattern during different cognitive processing in CCR. Firstly, the comparison between the orthography and checkerboard condition confirmed the existence of visual word form area in the left OTC[12], which in current study was located in left BA 19. It was also reported that BA 19 was tuned to phonological processing demands[13]. Hence, with fNIRS technique, we captured the cortical activation related to phonological processing when the subjects processed the orthographic stimuli. Since the orthographic stimuli and checkerboards were presented in the ratio of 2:1, the checkerboards, as the infrequent stimuli, might lead to the oddball effect, which caused the activation in bilateral OTC and resulted in the higher activation in right OTC activation compared to the orthography condition. Otherwise, we may expect an even higher activation elicited by the orthographic stimuli in the left OTC and a lower activation elicited by the checkerboards in the right OTC. Secondly, the real characters, which contained the high-level lexical information, was able to elicit higher brain activation for most of the channels, especially left BA19, compared to the pseudo characters. Importantly, these brain regions are related to not only phonological (left BA19) processing, but also the semantic processing (left STG, BA22).

Interestingly, real characters also evoked higher activation in right hemisphere. Considering that the functional difference between the real and pseudo character condition indicated the processing of high-level lexical information, including semantic and phonological information, we inferred that not only the left but also the right hemisphere were related to the high-level lexical information processing. The positive correlation between the relative activation and relative accuracy changes in pseudo character condition among multiple regions in bilateral STG, BA 19, and left fusiform gyrus also provided compelling evidence. In specific, increased activations in these regions enhanced the discrimination of pseudo characters from real characters. Meanwhile, the relative activation in left STG negatively correlated with relative changes of reaction time, which indicated that the engagement of semantic processing helped to speed up the discrimination of pseudo characters.

More importantly, the fNIRS technique not only differentiated the brain activation but also functional connectivity pattern during different cognitive processing in CCR. We analyzed the network differences by comparing the connectivity and nodal degree between conditions. Connectivity difference between orthography and checkerboard condition revealed that right BA 19 exhibited stronger connections with bilateral fusiform gyrus and left BA 19, which made right BA 19 an important hub in bilateral OTC network supporting the orthography processing. Besides, the connectivity between two different regions in right BA 19 in real character case was also stronger than that in pseudo character case. Therefore, we inferred that the right BA 19 might be the key hub in the brain network supporting the CCR. The comparison in nodal degree provided extra evidence for this claim. We discovered that right BA 19 owned higher nodal degree in orthography condition compared to checkerboard condition. Moreover, nodal degree changes in pseudo character condition influenced subjects' behavioral performance, which is indicated by the positive correlation between the relative nodal degree for pseudo character case in right BA 19 and the relative accuracy, as well as the negative correlation between the relative nodal degree in left STG and the relative . Thus, we provided thorough evidence that the right BA 19 might be the key hub in the brain network supporting the CCR.

In conclusion, the present study successfully mapped the hemodynamic response in the OTC during CCR by using fNIRS. The fNIRS technique is able to differentiate the brain functional activation and connectivity pattern during different cognitive processing in CCR. Our findings suggested that fNIRS is a promising tool for the investigation of Chinese language processing in occipitotemporal regions.

Acknowledgement

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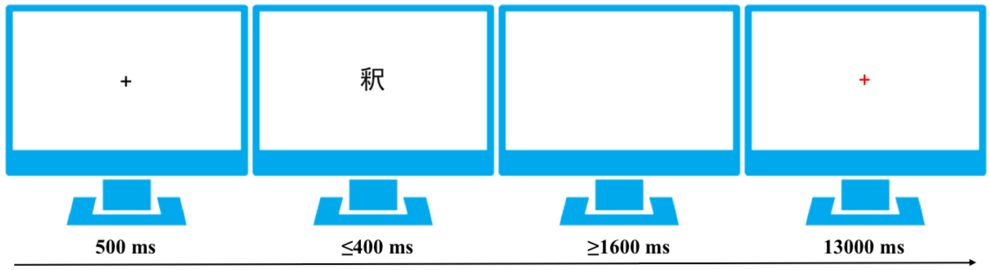

Fig. 1 An event-related design was adopted. Real characters, pseudo characters, and checkerboards were randomly presented. A trial began with a 500 ms black fixation, followed by a 400 ms stimulus. Participants were asked to determine whether the stimulus was a real character or not as soon as the stimulus appeared. Once the allowed key was pressed, the screen would turn blank. The response window was 1000 ms and followed by a 1000 ms blank screen. After that, there would be a red fixation indicating rest epoch, during which participants were asked to sit in stillness and watch the fixation to let the hemoglobin concentration back to baseline.

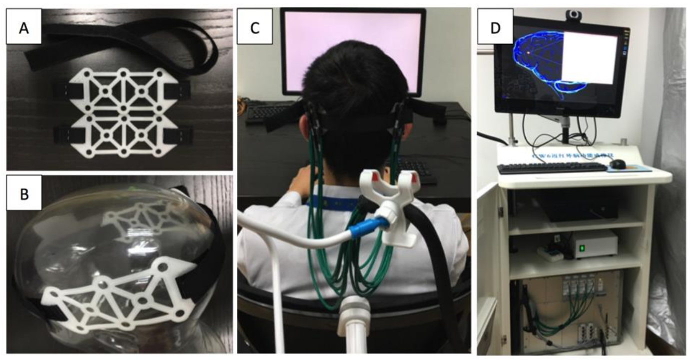

Fig. 2 (A) The patch used in the current study. (B) The position of patch indicated with a model-head. (C) Experimental scenario. (D) The CW6 fNIRS system used in the current study.

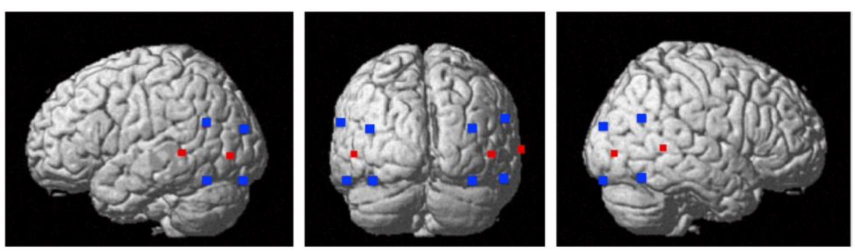

Fig. 3 The layout of the optodes in the left, posterior and right view. Red dots indicate the locations of sources, blue dots indicate the locations of detectors. Note that in posterior view, one source on the left side is missing due to the view angle.

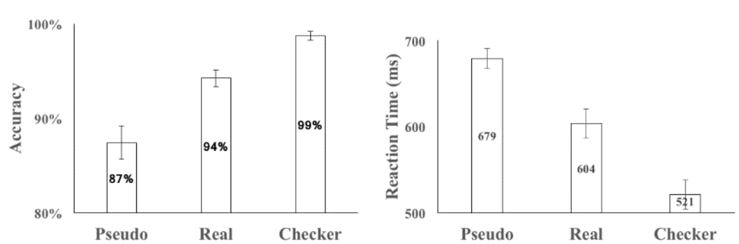

Fig. 4 The reaction time and accuracy in each condition. Each bar represents average ± 1 standard error.

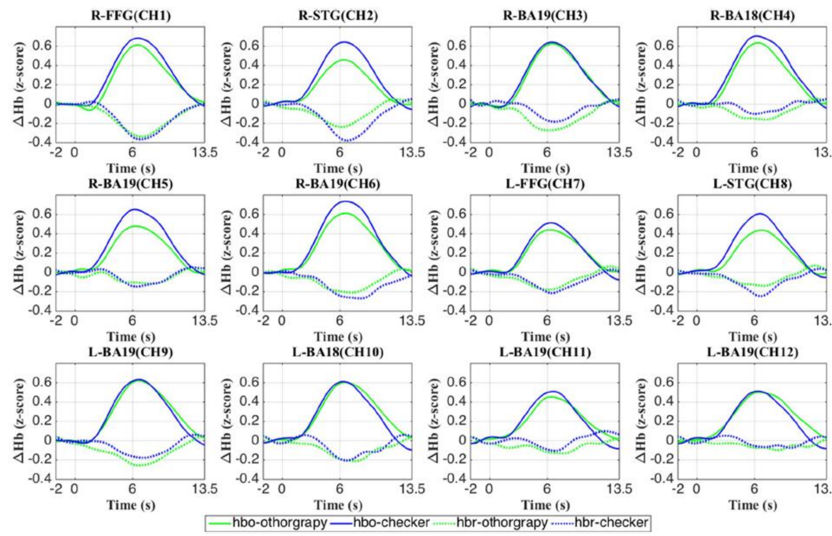

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Fig. 5 The time courses of the mean HbO and HbR changes (ΔHb, z-scores) associated with the orthography and checkerboard conditions for all the channels. In each channel, the solid curve indicates the mean z-scores of the HbO concentration changes, whereas the dashed curve denotes the mean z-scores of the HbR concentration changes. The green and blue curves indicate the orthography and checkerboard condition, respectively. The terms are listed as follows: R right hemisphere, L left hemisphere, FFG fusiform gyrus, STG superior temporal gyrus, BA Brodmann area, CH channel.

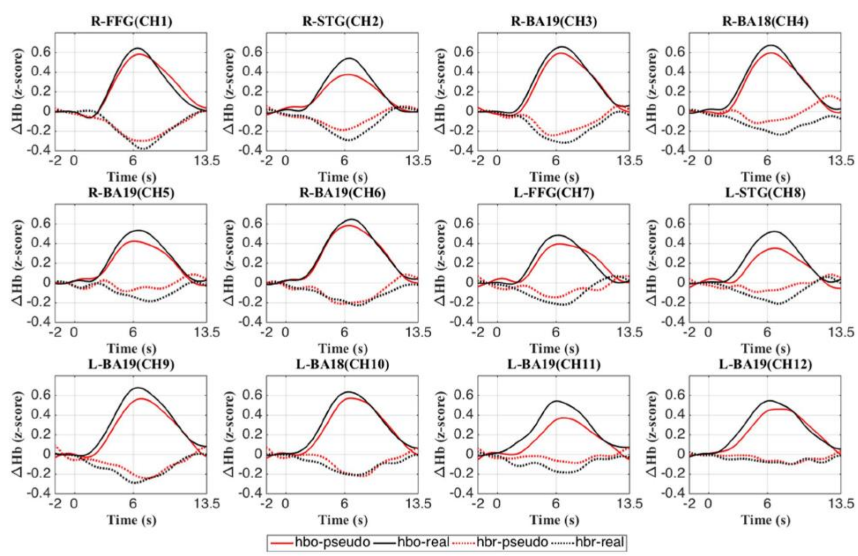

Fig. 6 The time courses of the mean HbO and HbR changes (ΔHb , z-scores) associated with pseudo and real character conditions for all the channels. In each channel, the solid curve indicates the mean z-scores of the HbO concentration changes, whereas the dashed curve denotes the mean z-scores of the HbR concentration changes. The red and black curves indicate the pseudo and real character condition, respectively.

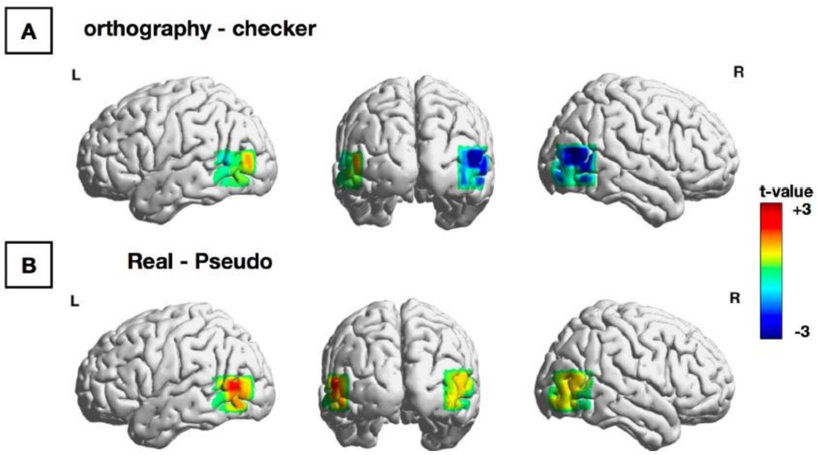

Fig. 7 Activation maps in the left, posterior and right view. Interpolated t-values from two contrasts, were rendered on the surface of brain templates, with brighter color representing that an orthographic stimuli elicited higher activation, or b real characters elicited higher activation.

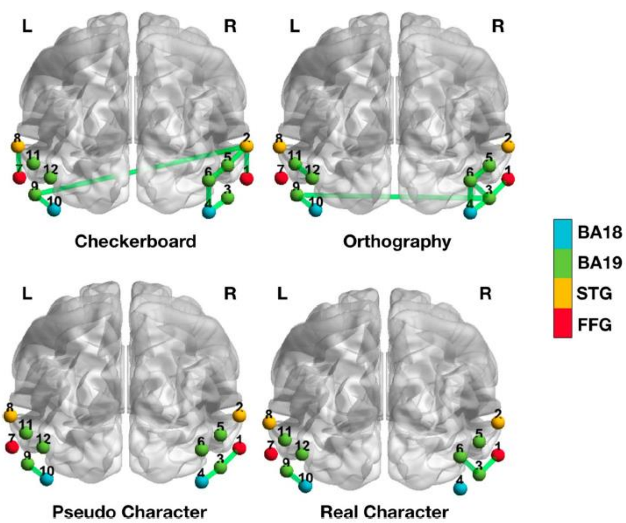

Fig. 8 Visualization of the relationship between channels under different conditions. Channels and connectivity are visualized on a brain template, in which channels are indicated by dots with different colors representing different brain regions and labeled with numbers, and the connectivity above the threshold of 0.95 are indicated by green lines.