Effects of mental rotation on map representation in orienteers - evidence from behavioral and fNIRS

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Background. People are constantly engaged in way-finding in their daily lives. The success of way-finding navigation depends on the accuracy of real-world and map representations. The purpose of this study was to examine the effects of mental rotation on learners' map representations and their brain processing characteristics using an orienteering sport program. **Methods.** Functional near-infrared spectroscopic imaging (fNIRS) was used to explore the behavioral performance and changes in cortical oxyhemoglobin concentration during cognitive processing of map representations in orienteers under two task conditions normal orientation and rotational orientation. **Results.** The task performance of practitioners in the rotational orientation condition was significantly decreasing compared to the normal orientation. In the normal orientation, dorsolateral prefrontal activation was significantly greater than ventral lateral prefrontal activation, which was significantly correlated with correct rate; as the rotational orientation was rotated, cerebral oxygen water averaged across regions of interest, and the brain region specifically processed was ventral lateral prefrontal, which was significantly correlated with correct rate. **Conclusions.** Mental rotation constrains orienteers' map representation ability, and map representation in rotational orientation requires more functional brain activity for information processing, and ventral lateral prefrontal activation plays an important role in the map representation task in rotational orientation.

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Abstract

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Methods. Functional near-infrared spectroscopic imaging (fNIRS) was used to explore the behavioral performance and changes in cortical oxyhemoglobin concentration during cognitive processing of map representations in orienteers under two task conditions normal orientation and rotational orientation.

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Conclusions. Mental rotation constrains orienteers' map representation ability, and map representation in rotational orientation requires more functional brain activity for information processing, and ventral lateral prefrontal activation plays an important role in the map representation task in rotational orientation.

Keywords: map representation; mental rotation; near-infrared functional brain imaging (fNIRS);orienting movement; prefrontal cortex

Introduction

People are constantly engaged in way-finding in their daily lives. The success of way-finding navigation depends on the accuracy of real-world and map representations. Orienteering is a sport in which maps and compasses are used as navigation tools, map information is identified and matched with real-world environmental information, and checkpoints are visited as required by the competition[1-2]. It can be said that the core of orienteering is way-finding navigation. The ability of map representation is an important guarantee for completing the race[3], mainly in terms of the practitioner's ability to quickly identify map information and match it with the real scene. It is necessary to analyze map information with existing knowledge and experience, extract the characteristics of map symbols, integrate and process them, and match them with external environmental information simultaneously to calibrate the map and find the target. The whole process involves a variety of spatial cognitive processing such as attention, memory and mental rotation[4]. By exploring the performance of map representations of orienteers, it will further reveal the cognitive processing of map representations, promote the scientific training of orienteering programs, and provide theoretical support for the training model of deliberate practice for this program to enhance the improvement of practitioners' way-finding and navigation abilities.

The orientation of the map and the field are usually different in the process of map representation. The rotational orientation keeps changing, and one must constantly adjust the positional relationship between the map and the reference[5] to match with the real-world information. The brain needs to re-represent the map to form a mental image map, which requires a good mental rotation ability [6]to assist practitioners in spatial orientation to accurately and quickly match the real scene. Eccles (2002a) used the rooting theory method to propose that the orientation map[7], real scene information and visual attention during travel are the core factors of the project, and scene recognition efficiency is affected by rotational orientation[8], which in turn affects route decision efficiency, and mental rotation ability is strongly correlated with task performance[9-10], constraining map recognition and spatial orientation. Therefore, this paper explores the cognitive mechanisms underlying the effects of mental rotation on the processing of perceptual information of map representations through map and real-world recognition of directed movements.

Functional near-infrared spectroscopy imager (fNIRS) is an emerging brain functional imaging technique that uses a near-infrared light source that penetrates human tissues to detect changes in the concentration of HbO2 and HbR, the major absorbers of near-infrared light[11-12], and is able to indirectly quantify neural activity, which provides this study's technical support for the study of cognitive processing characteristics of map representations. Brain imaging technology has unique advantages such as high safety performance, portability, high spatio-temporal resolution, and less influence by head movement[13], and is now widely used in sports research involving soccer[14], badminton[15], taijiquan[16]and other sports. The prefrontal-cortical area (Prefrontal-corterx, PFC) is the most anterior region of the frontal cortex, accounting for about half of the frontal lobe, located in the area before the central sulcus and above the lateral sulcus, and is closely connected to brain regions such as the parietal, occipital, and temporal lobes. During information processing in the brain, most of the multiple information from various brain regions is finally aggregated in the prefrontal cortex area, which does the final processing, integration and processing[17], the area responsible for higher cognitive activits such as motivation, problem solving, thinking and judging, and planning[18-21]. Therefore, in this study, the prefrontal cortex (PFC) was selected as the main functional area, and four areas of interest were delineated based on the existing research results of 3D localization, namely: dorsolateral prefrontal lobe (DLPFC), frontopolar area (FOA), ventral lateral prefrontal lobe (VLPFC), and box frontal area (OFA). Currently, directed movement cognitive studies have focused on behavioral tests of cognitive indicators such as visual attention[22], working memory[23], and mental rotation[9]. On the other hand, interventions through orienteering exercises were all found to have some intervention benefits on the cognitive abilities of primary and secondary school students, children with ADHA, people with intellectual disabilities, and the elderly[24-27]. However, previous studies have only illustrated the cognitive processing performance of orienteering sports programs at the behavioral level and the intervention benefits for specific groups, lacking the exploration of brain neural mechanisms of cognitive processing characteristics and benefits.

To address the above questions this study further explored the mechanisms of brain processing action in a map representation task with the help of fNIRS technology. The following hypotheses were proposed: (1) orienteers would show different behavioral performance under different mental rotation tasks. (2) Behavioral outcomes are correlated with cerebral blood oxygen outcomes. Mental rotation causes differences in HbO2 activation over regions of interest in a map representation task. Through the study, the blood oxygen response patterns of map representations in different brain regions under the mental rotation task were explored to provide an objective basis for future enhancement of map representation task performance through neuromodulation, and to provide theoretical support and practical guidance for the benefits of different intervention models of orienteering exercises to improve cognition.

Materials & Methods

1.Experimental subjects

Thirty-three (15 male, age 20.47±0.99, 18 female, age 19.72±13.13) varsity orienteering players from a university with 3.16±0.56 years of training were selected for the experiment. the following inclusion criteria were used for all subjects: (1) consistent education; (2) all right-handed; (3) normal vision; (4) no history of any neurological disease; (5) be able to master the specific skills of orienteering relatively proficiently; (6) not have participated in similar experiments before. Remuneration will be given upon completion of the experiment, which sought the consent of the subjects and signed an informed consent form, and the study was approved by the ethics and morality committee of Shaanxi Normal University (Approval number: SNNU2023301). Informed consent was obtained from all participants for this study(supplementary materials).

2. Experimental design and materials

A 2 × 4 two-factor mixed design was used for the experiment. Factor 1: task condition (normal and rotational orientation), factor 2: brain regions of the prefrontal lobe: dorsolateral prefrontal lobe (DLPFC), frontal polar region (FOA), ventral lateral prefrontal lobe (VLPFC), and Orbitofrontal region (OFA). Dependent variables: behavioral indicators (correctness, reaction time) characterized by different rotational position maps of the subjects and the concentration of oxyhemoglobin (HbO2) in each brain region of the prefrontal lobes.

The stimulus material consisted of an orienteering map and a corresponding real-world photo, including map information, a checkpoint description sheet (detailed information describing the location of points in the map), a pointing sign, and a real-world photo. The map was divided into normal orientation (consistent orientation) and rotated orientation (inconsistent orientation) according to the degree of matching with the orientation of the real-world photo, and there were four choice locations in the real-world photo (indicated by white and orange dot marker flags), one of which was the correct option consistent with the map dot location. As shown in Fig 1 (left), the map point number is 31, the checkpoint description table indicates on the left side of the special feature, the north pointing marker shows the map orientation consistency, the correct option in the live photo should be point 1. All stimulus materials of the experiment were produced, screened and proofread by three orienteering specialists.

3 .Experimental equipment

A portable functional near-infrared spectroscopic imager (LIGHTNIRS system) manufactured by Shimadzu Corporation, Japan, was used to monitor the oxyhemoglobin (HbO2),

deoxyhemoglobin (HbR), and total blood oxygen concentration were monitored, and HbO2 is more sensitive to local blood flow changes in the brain compared to HbR, therefore, HbO2 was selected to reflect the level of neural activation in the brain in this study [28-30].
The photo-polar probe was located in the prefrontal lobe (PFC), and the lowest probe was placed along the Fp1-Fp2 line using the international 10-20 localization system as a reference, using the system's own PFC template, with a multi-channel connected layout of 2 × 8 photo-polar probes (8 transmitting and 8 receiving photo-poles), forming a total of 22 channels, with two similar photo-poles lined up at intervals and a distance of 3 cm between adjacent photo-poles. using a 3D digital The MNI position coordinates of each channel position were determined by the NIRS_SPM software spatial probability alignment method, and the corresponding brain areas were found in the adult Brodmann area (Brodmann) atlas, and the calibration information is shown in Fig 2.

4.Experimental procedure
Before the experiment, the subjects were allowed to familiarize themselves with the experimental environment, and relevant information such as gender, age, training duration, and exercise level were recorded. Subjects were informed of the experimental precautions during the experiment. The subjects were instructed by the experimental staff to wear fNIRS optical polar caps, adjusted to the appropriate looseness and then fixed with nylon buckles, and positioned for calibration. Then the optical fiber was inserted into each probe to check whether the light emission and reception of each channel were normal, and after the signal of each channel was stabilized, the zero reset was performed and the measurement started. Two tasks were included for testing (normal orientation and rotational orientation) with the same operational procedure.
The experimental stimuli were prepared with the help of the neuropsychological programming software "E-prime 3.0" and consisted of a practice phase and a formal experiment. First, the instructions were presented on the complete computer screen, and the subjects were asked to familiarize themselves with the task and the procedure, and then to press the space bar to practice, then a gaze point was presented for 1 second, followed by the stimulus picture, and the subjects had to carefully observe the picture information, select the option with the same position in the real photo according to the map orientation and point location, and press the corresponding numeric key according to the checkpoint description sheet. Subjects were given 6 seconds to make a judgment, and feedback on the results was given after the judgment was completed, and the test process is shown in Fig 3:
In the formal test phase, the resting state electrophysiological signal is first collected for 30 seconds and the subject remains relaxed. Then the test task started, the same process as in the practice phase, but the subject did not receive feedback after making a judgment, and the stimulus was presented cyclically until the end of the test. Every 4 trials constituted a block, 6 blocks in total, with a rest of 20 seconds between each block (to ensure that the relative concentration of cerebral blood oxygen in the PFC returned to the baseline value), for a total of 24 trials (as shown in Fig 4), and the program automatically recorded the reaction time and correct rate of the subject doing the task, and the NIR device collected cerebral blood oxygen data.

5.Data collection and analysis
Behavioral data: SPSS 26.0 was used to test the measurement data for normal distribution, which was greater than 0.05 threshold, indicating that it obeyed normal distribution; the correct rate of

map representation and response time of subjects under two different rotational orientations were observed by paired samples t-test to observe the differences of behavioral indicators under different rotational orientations. Differences in behavioral metrics were observed for different rotational orientations.

fNIRS data: The raw data collected were solved by using the fNIRS device's own software, based on the NIRS_SPM software of Matlab (R2013b) platform. The light intensity data were converted to blood oxygen data by the modified Beer-Lambert law, and then the data were pre-processed to eliminate outliers and improve the signal-to-noise ratio, so that the overall filtered signal was easy to analyze for subsequent calculations. This includes: MNI coordinate alignment; construction of the design matrix based on the general linear model (GLM); low-pass filter based on the hemodynamic response function (HRF) with time derivatives; high-pass filter based on the discrete cosine transform (DCT) detrending algorithm; and then the Beta value under the task conditions is evaluated as the activation index of the corresponding channel. Finally, the beta of each channel contained in the region of interest (ROI) is averaged, and this average value is the activation intensity of this region of interest (ROI) [31-32]. The cerebral blood oxygen data were tested for normal distribution using SPSS 26.0, and the Shapiro-Wilk test (S-W) test showed that the data were greater than the 0.05 threshold, indicating that they obeyed a normal distribution; then a two-task condition (normal orientation, rotational orientation) × 4 (VLPFC, DLPFC, FOA, OFA) two-factor repeated measures ANOVA was performed, and statistics that did not satisfy the sphericity assumption Quantities were corrected by the Greenhouse method, and further tests were performed using the Bonferroni method for multiple corrections, with $p < 0.05$ considered as significant differences. Bivariate correlations between behavioral data and cerebral blood oxygen data were analyzed by GraphPad Prism 8.0 for 1) correct rate of normal orientation map representation with cerebral blood oxygen (4 brain regions of interest) and 2) correct rate of rotational orientation map representation with cerebral blood oxygen (4 brain regions of interest), respectively.

Results

1.Behavioral data results

The results of descriptive statistics of correctness and response time for map representations with different rotational orientations are shown in Table 1.

Table 1. Results of behavioral indicators of map representation (M±SD).

	Correct rate	Reaction time (ms)
Normal orientation	0.67±0.053*	3718.285±346.790**
Rotational orientation	0.54±0.065*	3910.818±369.414**

(Note: * represents $0.001<p<0.05$,** represents $p\leq0.01$)

Paired-samples t-tests were conducted on the behavioral data of map representations in normal and rotational orientations, and the results showed that the correctness of map representations differed significantly, with normal orientation significantly higher than rotational orientation, with a t-value of 2.946 ($p=0.006<0.05$); the response time of map representations differed significantly, with normal orientation significantly lower than rotational orientation, with a t-value of 5.190 ($p=0.000< 0.01$).

2.fNIRS data results

A two-factor repeated-measures ANOVA was performed on the beta values of cerebral blood oxygen (HbO2) of the subjects in the 2-task condition (normal orientation, rotational orientation) × 4 brain regions (DLPFC, FOA, VLPFC, OFA) using rotational orientation and brain region of interest as independent variables, and the results are shown in Table 2 and Figs 5 and 6 below.

Table 2. Statistical results of HbO2 description of the map-represented brain regions of interest (M±SD) × 10^{-3}.

	DLPFC	FOA	VLPFC	OFA
Normal orientation	-0.65±2.61**	-1.19±2.80	-2.22±4.71**	-1.83±6.10
Rotational orientation	1.26±2.76**	-0.46 ±2.52	1.42±3.67**	-0.97±3.46

(Note: * represents 0.001<p<0.05,** represents p≤0.01)

The results showed that the main effect of brain area was not significant $F(3, 29)=2.027$, $p=0.126$, $\eta2=0.177$; the main effect of rotational orientation was significant $F(1, 31)=13.367$, $p=0.001<0.05$, $\eta2=0.177$; the interaction between brain area and rotational orientation was significant $F(3, 29)=3.333$, $p=0.033$, $\eta2= 0.256$, and the results of the simple effects analysis indicated that.

In the dorsolateral prefrontal lobe (DLPFC) and ventral lateral prefrontal lobe (VLPFC), significant differences in oxygen activation emerged between the two rotational orientations, as demonstrated by significantly higher oxygen activation in the rotational orientation than in the normal orientation, with F values of 11.330, ($P=0.002$, $\eta2= 0.268$) and 13.487, ($P=0.001$, $\eta2= 0.303$), respectively.

In the normal orientation condition, blood oxygen activation was significantly greater in the dorsolateral prefrontal lobe (DLPFC) than in the ventral lateral prefrontal lobe (VLPFC) [$P=0.044$, $\eta2=0.139$]; in the rotational orientation condition, there was no significant difference in blood oxygen activation in the dorsolateral prefrontal lobe (DLPFC) and ventral lateral prefrontal lobe (VLPFC) ($P=0.851$, $\eta2=0.324$), and both brain regions were significantly greater than the frontopolar area (FOA) [$P=0.004$, $P=0.010$] and orbitofrontal area (OFA) [$P=0.014$, $P=0.004$]. This result suggests that the ventral lateral prefrontal lobe (VLPFC) becomes more activated by blood oxygen in the map representation task in rotational orientation.

3.Correlation analysis of correctness and activation intensity of brain interest areas

The degree of correlation is generally expressed as a correlation coefficient r with values between -1 and 1. A value greater than 0 indicates a positive correlation and less than 0 indicates a negative correlation. r in the range of 0 to 0.30 indicates a low correlation, 0.31 to 0.49 indicates a moderate correlation, 0.5 to 0.69 indicates a high correlation, and 0.7 to 0.89 indicates a very high correlation33. The behavioral performance (correctness) of the two tasks was correlated with cerebral blood oxygen (HbO2) beta values in different brain regions to explore the degree of correlation between activation intensity and behavioral performance, as shown in Table 3 and Fig 7.

Table 3. Correlation results between fNIRS and behavior (Pearson correlation coefficient r).

Indicators	Correlation	DLPFC	FOA	VLPFC	OFA

Normal orientation correct rat	Pearson correlation	0.404*	0.106	0.295	0.280
	Significance (two-tailed)	0.022	0.562	0.105	0.121
Rotation orientation correct rate	Pearson correlation	0.356*	0.262	0.494**	0.050
	Significance (two-tailed)	0.045	0.148	0.004	0.784

(Note: * represents significant correlation at the 0.05 level;
** represents significant correlation at the 0.01 level)

The results showed that the correct rate of normal orientation was significantly and positively correlated with the dorsolateral prefrontal lobe (DLPFC) [P=0.022<0.05, r=0.404] and not with any other brain regions; the correct rate of rotational orientation was significantly and positively correlated with the dorsolateral prefrontal lobe (DLPFC) [P=0.045<0.05, r=0.356], ventral lateral prefrontal lobe (VLPFC) [P= 0.004<0.05, r=0.494] were significantly and positively correlated with the frontopolar area (FOA) and orbitofrontal area (OFA), and not with the orbitofrontal area (OFA).

Discussion

1.Behavioral characteristics of map representations

The results of the study showed that the behavioral performance of map representations with different rotational orientations differed significantly, as evidenced by significantly lower correct rotational orientation rates and significantly higher reaction times, indicating that rotational orientation increases the cognitive load of orienteers. In the process of map representation, the input map information is first identified, and further processed and analyzed according to the information recorded by the brain and key factors to identify the stimuli, including perception, attention, memory, matching, etc. This process is to prepare for the match with the real scene. Whereas rotational orientation requires subjects to mentally rotate and re-represent the features of the rotated real scene, the brain then needs more time to think about the correct reference point information, making recognition processing consume more cognitive resources and thus longer reaction times[34], consistent with previous findings[35].

2.Brain activation mechanisms of map representations

The process of recognizing object orientation and location requires cognitive processing of the object. According to cognitive load theory, an individual's cognitive resources are limited, and when the difficulty or number of tasks increases, the cognitive load on the individual increases, requiring the individual to extract significantly more relevant cognitive resources[36]. Under normal orientation, the task is relatively simple, and the individual's spatial cognitive processing is easier in terms of resource allocation to relevant brain regions, and the mobilization of attentional resources is not too difficult[37], while rotational orientation requires more cognitive effort to complete the task. The more complex the information processing, the greater the impact on the final performance[38]. Rotation of orientation makes recognition processing consume more attentional resources, and the individual's correct rate decreases[39]. orienteers' information processing for rotational orientation, which requires integrated analysis of checkpoint description table information and map information, mental rotation and abstract three-dimensional imagery, would require more cognitive resources to allocate, which would show a decrease in the correct rate of map representations and manifest in this indicator at reaction time.

Kelly et al. argued[40] that the degree of involvement of DLPFC depends on the cognitive features of the task performed and is the main functional area for spatial information retention, monitoring, and cognitive decision making[41-42], and the map representation process involves the recognition, encoding, and representation of map information as real-world information, which requires the practitioner's spatial cognitive ability with high requirements. Therefore, the activation of DLPFC brain regions is greater than other brain regions under normal orientation conditions. Hikosaka (2002) pointed out that DLPFC involves spatial location acquisition, processing initial perceptual input and spatial sequence depiction, and spatial information of rotational orientation requires more spatial sequence depiction and more cognitive effort[43], so the oxygenated hemoglobin concentration in DLPFC brain regions increased, i.e., the intensity of cerebral blood oxygen activation increased. Another study noted that when the excitation of DLPFC brain regions was disrupted, subjects were found to be more responsive to spatial information processing tasks, and the DLPFC was also significantly activated when the complexity of the task process, and integration demands became greater[44]. The results of the present study also showed that the activation of the DLPFC brain region was significantly greater in rotational orientation than in normal orientation, further validating the function of this brain region from task-specific scenarios.

VLPFC brain regions were significantly more activated in the rotational orientation condition than in the normal orientation, which may be due to the fact that rotational orientation requires subjects to perform mental rotation, re-represent and manipulate the spatial relationships of objects, construct a rotated visual representation in the brain, and match the "north" of the map with the "north" of the real scene. ", increasing the cognitive processing task. Previous studies have also pointed out that the VLPFC brain region, together with other related regions (i.e., the angular and cingulate gyrus, posterior pleural cortex), constitutes the so-called "default mode network" and suggests a vision of the future and memory retrieval that is closely related to human navigation processes and involves functions such as control of orientation perception and map representation, as well as spatial attention, and key areas of scene memory[45-47]. In the rotational orientation condition, orienteers need to rotate themselves in the environment or treat the environment as an overall rotating external entity, a process that requires athletes to reorient themselves spatially, increasing the difficulty of the task, and the VLPFC brain region is significantly activated as a major functional area with some advantageous processing.

The dominance of activation of FOA brain regions remains unclear, and multiple hypotheses exist. It has been suggested that with the onset of aging, cognitive ability gradually decreases and cognitive processing slows down significantly, that the activation of FOA brain regions is significantly enhanced in older adults compared to younger adults who face higher complexity in the same task, and that older adults probably use compensatory strategies to complete more complex information processing, showing compensatory mechanisms of brain processing[48]. The prefrontal theory of function also suggests that information processing is posterior-to-forward in this region, with the frontopolar region at the top of the hierarchy, and that the frontopolar region is recruited to function only when the low-functioning system fails[49]. the OFA brain region mainly regulates some higher cognitive functions, such as reward judgment, working memory, risk assessment, emotional adjustment, and other neural activities, and individuals rely on this brain region in risk aversion are dependent on this brain region[50-51]. In the present study, there were no significant differences in the activation of FOA and OFA brain regions under both orientation tasks.

The cognitive processing pathway hypothesis states[52] that cognitive processing mainly consists of two different cortical processing channels, one is the ventral pathway (what pathway) and the other is the dorsal pathway (where pathway). The dorsolateral prefrontal lobe (DLPFC) and ventral lateral prefrontal lobe (VLPEC), as the main functional areas of prefrontal cortex, are closely related to brain functions related to motor cognition. In the map representation process, which involves inputting, encoding, storing and extracting map information, and finally matching it with the real scene, rotational orientation has relatively more orientation changes than normal orientation during cognitive processing, which may result in enhanced network connectivity between brain regions under rotational orientation conditions. activation of VLPFC brain regions is significantly correlated with correctness, and the complexity of the task becomes greater, requiring more brain regions to cooperate with athletes to complete the map representation task. This study identified important roles of DLPFC and VLPFC brain regions in rotational orientation, which will provide an objective basis for improving practitioners' map representation ability through orienteering training in the future.

Conclusions

The study examined the changes of behavioral performance and prefrontal activation of map representation in Orienteers by mental rotation using fNIRS instrument, and found that the behavioral performance ability of map representation decreased with orientation rotation, and the functional activation of dorsolateral prefrontal and ventral lateral prefrontal appeared significantly more important, and it was also found that more brain regions were involved in cognitive tasks and the synergistic effect of each brain region increased under rotation condition, which concluded that The findings provide theoretical support for the scientific training of orienteering sports programs and the construction of a training model to promote the improvement of wayfinding navigation ability.

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Table 1(on next page)

Results of behavioral indicators of map representation.

Table 1 Results of behavioral indicators of map representation (M±SD)

	Correct rate	Reaction time (ms)
Normal orientation	0.67±0.053*	3718.285±346.790**
Rotational orientation	0.54±0.065*	3910.818±369.414**

(Note: * represents 0.001<p<0.05,** represents p≤0.01)

Table 2(on next page)

HStatistical results of bO2 descriptions for map-represented regions of interest in the brain.

Table 2 Statistical results of HbO2 description of the map-represented brain regions of interest (M±SD) × 10^{-3}

	DLPFC	FOA	VLPFC	OFA
Normal orientation	-0.65±2.61**	-1.19±2.80	-2.22±4.71**	-1.83±6.10
Rotational orientation	1.26±2.76**	-0.46 ±2.52	1.42±3.67**	-0.97±3.46

(Note: * represents $0.001<p<0.05$,** represents $p\leq0.01$)

Table 3(on next page)

Correlation results between fNIRS and behavior (Pearson correlation coefficient r).

Table 3 Correlation results between fNIRS and behavior (Pearson correlation coefficient r)

Indicators	Correlation	DLPFC	FOA	VLPFC	OFA
Normal orientation correct rat	Pearson correlation	0.404*	0.106	0.295	0.280
	Significance (two-tailed)	0.022	0.562	0.105	0.121
Rotation orientation correct rate	Pearson correlation	0.356*	0.262	0.494**	0.050
	Significance (two-tailed)	0.045	0.148	0.004	0.784

(Note: * represents significant correlation at the 0.05 level; ** represents significant correlation at the 0.01 level)

Figure 1

Example of different orientation maps.(A)

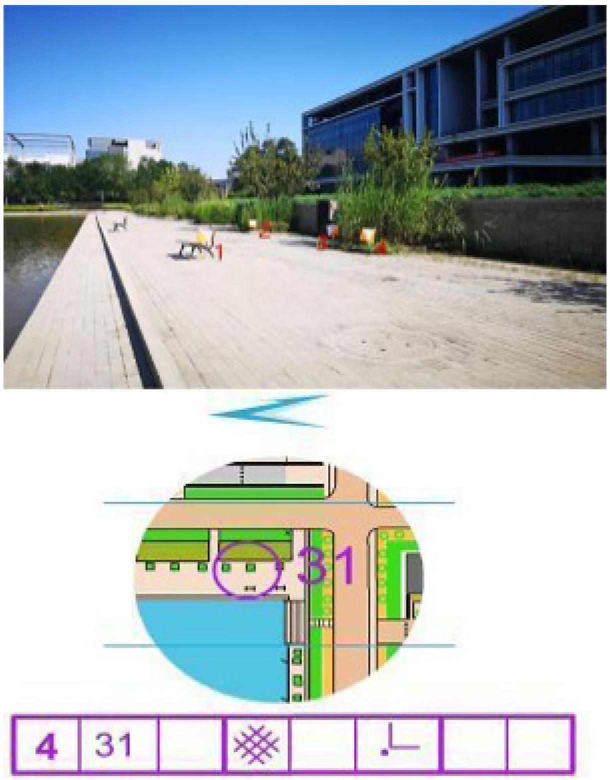

Figure 2

Example of different orientation maps.(B)

Figure 3

fNIRS channel layout and information of calibrated brain regions.

red indicates emitter-source, blue indicates detector-detector, and numbers indicate -channel

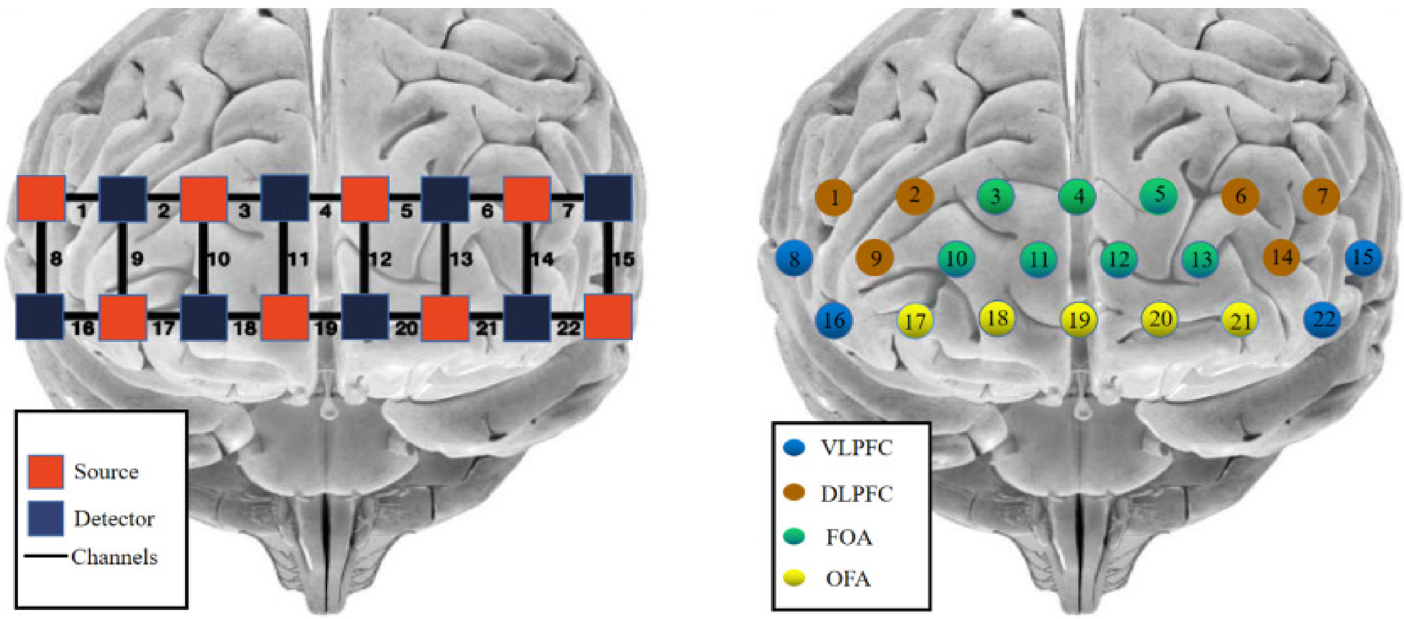

Figure 4

fNIRS test process.

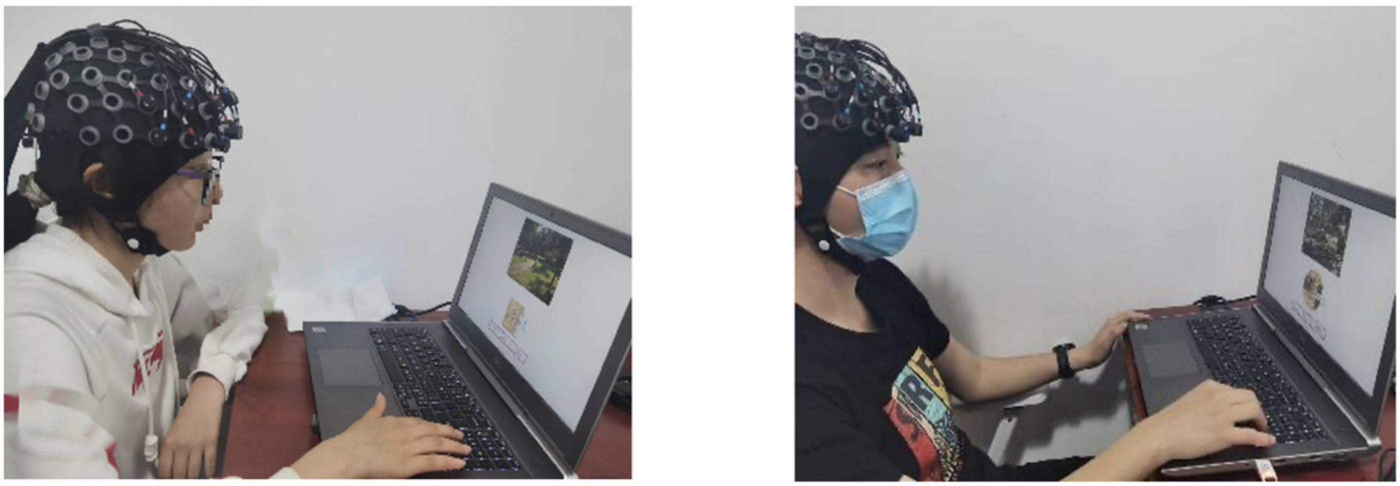

Figure 5

Experimental flow chart.

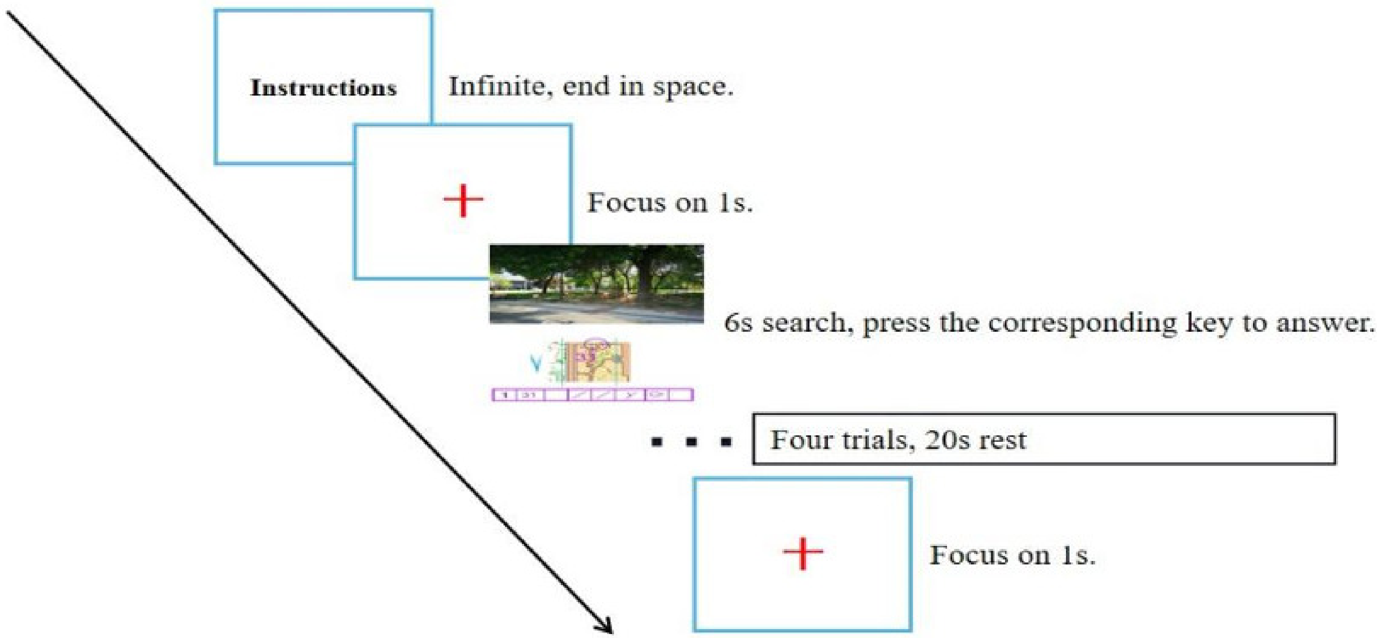

Figure 6

HbO2 results for the map-represented brain regions of interest.

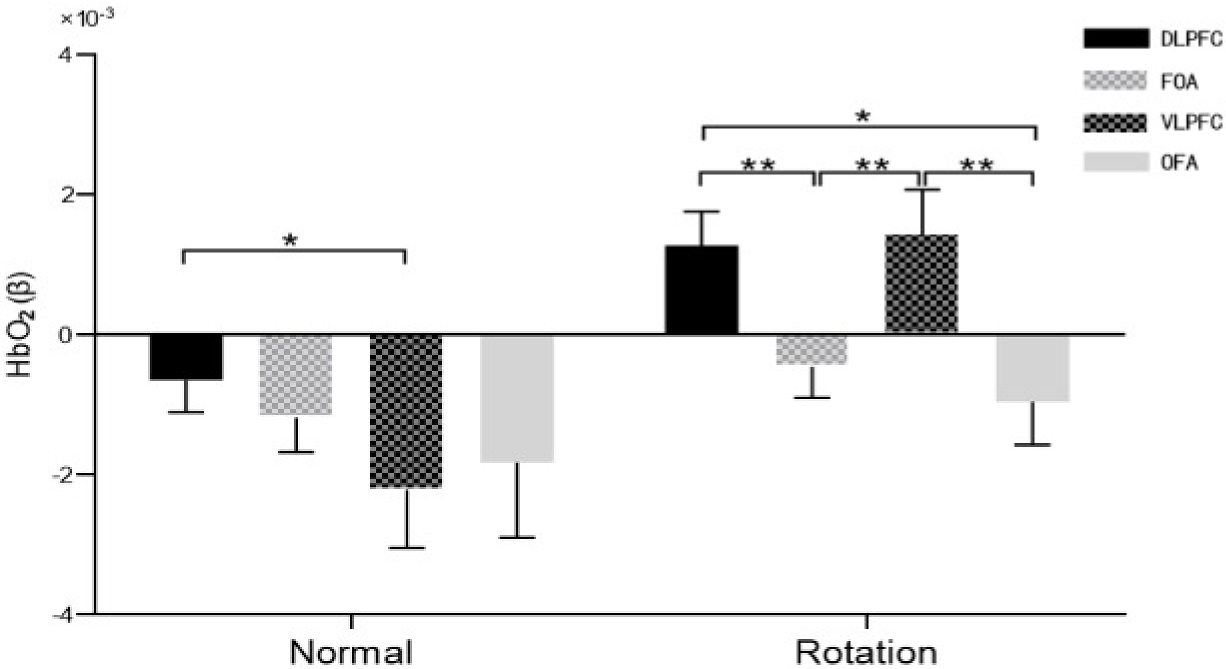

Figure 7

A map representation of the activation map of HbO2 values in the brain. (A)

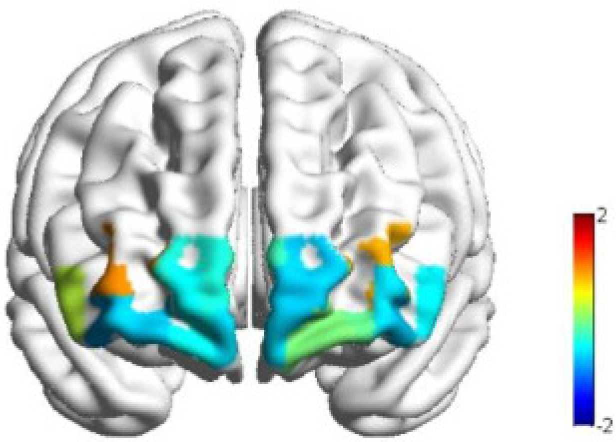

Figure 8

Map representation of HbO2 value activation maps in the brain.(b)

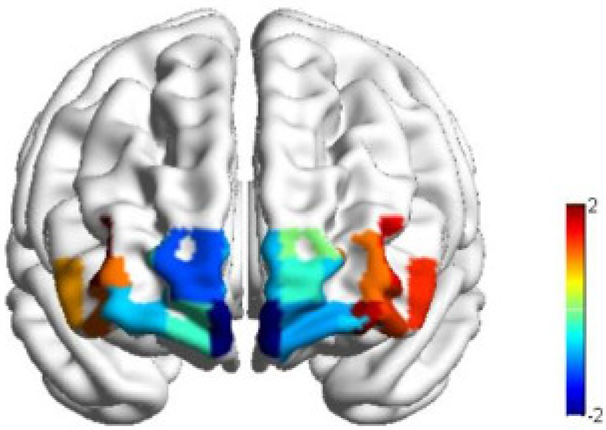

Figure 9

Map characterizing the correlation between HbO2 valuesand correctness in the brain area of interest.(A)

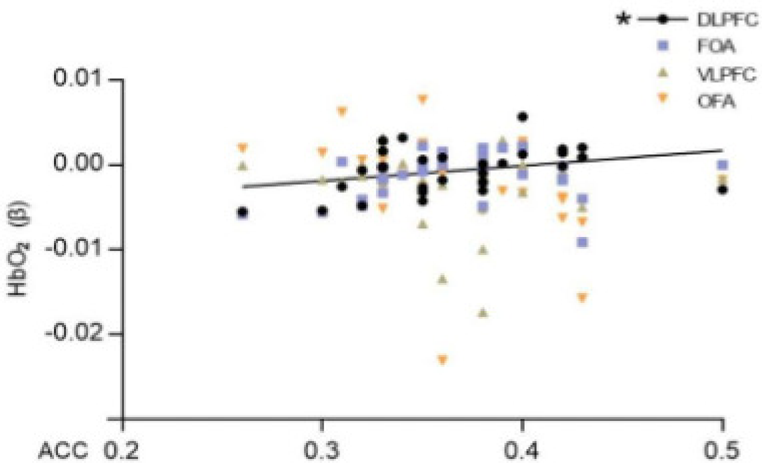

Figure 10

Map characterizing the correlation between HbO2 valuesand correctness in the brain area of interest.(B)