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# Interactive Effects of Orienteering Experience and Cognitive Performance on Dynamic Prefrontal Activation: An fNIRS Study Using a Maze Task

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# Abstract

This study aimed to explore the regulatory effect of orienteering experience on spatial cognitive performance in non-specialized scenarios and the underlying neural activation mechanisms of the prefrontal cortex. Forty male orienteers were recruited as participants and divided into an expert group (n = 20) and a novice group (n = 20). A gradient-difficulty octagonal maze task was adopted as the spatial cognitive paradigm, and functional near-infrared spectroscopy (fNIRS) was utilized to simultaneously record behavioral data and oxyhemoglobin ($HbO_2$) signals from the bilateral prefrontal cortex. The results revealed two core findings. At the behavioral level, the expert group achieved significantly higher accuracy and shorter total response time across all maze difficulty levels compared with the novice group, and a significant interaction effect between task difficulty and orienteering experience was observed for behavioral performance. At the neural level, the expert group exhibited markedly stronger $HbO_2$ activation in the dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC), with a more focused activation pattern as task difficulty increased. Correlation analyses demonstrated that DLPFC activation intensity was significantly positively correlated with task accuracy and significantly negatively correlated with total response time. This study indicates that long-term orienteering training optimizes prefrontal neural efficiency and improves spatial memory and route decision-making capacity, providing empirical neurobiological evidence for the cognition-enhancing effects of physical exercise.


# Introduction

Spatial memory constitutes a core high-order cognitive faculty in humans, closely linked to a range of neural cognitive processes including spatial representation, environmental navigation, pathfinding, and dynamic decision-making. It serves as a fundamental prerequisite for individuals to adapt to surroundings and engage in spatially oriented survival behaviors [1–2]. Since Tolman put forward the concept of the “cognitive map” in 1948, the formation mechanisms and processing characteristics of spatial memory have remained a central research focus in cognitive neuroscience [3]. As the foundation for consolidating all forms of cognitive processing, spatial memory essentially refers to the encoding, storage and retrieval of geographic bearings and spatial layouts of external environments. It is categorized into spatial working memory, short-term spatial memory and long-term spatial memory, which jointly determine an individual’s capacities for spatial perception, environmental recognition and route planning [4–6].

Mature experimental paradigms have been established for investigating spatial memory, among which the Corsi block tapping test, N-back task and spatial span task are the most widely adopted protocols. These tasks mostly utilize regular geometric figures and simple stationary objects as experimental stimuli [7–8]. Although they can reliably measure basic spatial memory performance, they suffer from limited ecological validity and fail to faithfully replicate the patterns of spatial navigation and environmental memory observed in real-world scenarios [9–10]. Against this backdrop, the present study

adopts maze maps as experimental stimuli, which can objectively reflect real-life spatial memory capacity and precisely reveal the practical value of spatial memory during navigational behaviors.

Existing literature has documented prominent individual disparities in spatial memory ability, yet the regulatory mechanisms of athletic experience on spatial cognition remain insufficiently elucidated [11]. Multiple studies have verified that specialized athletic training can improve spatial memory performance, alongside faster response speeds and higher judgment accuracy during cognitive tasks [12]. Nevertheless, the disparities in cognitive processing and neural activation between individuals with varying levels of athletic expertise have not been fully characterized [13]. Therefore, systematic research is required to unpack the behavioral and neural distinctions in spatial cognition shaped by different levels of athletic experience [14].

Orienteering represents an aerobic sport accompanied by high cognitive load [15], integrating the physical endurance demands of endurance events and the strategic thinking requirements of tactical sports [16]. Described as a discipline that “combines marathon-level physical stamina with the strategic thinking of chess”, orienteering delivers stronger cognitive intervention benefits compared with conventional aerobic exercise [17–19]. During competitions, orienteers are required to complete environmental identification, visual search, route planning and dynamic decision-making in unfamiliar terrains with the aid of maps and compasses [20–21]. Long-term specialized training cultivates efficient spatial cognitive strategies and continuously strengthens individuals’ directional perception, spatial memory and instantaneous decision-making skills [22–24].

The rapid advancement of functional near-infrared spectroscopy (fNIRS) has propelled research on sport cognition beyond traditional behavioral observations toward dynamic measurements of cortical neural activation [25]. Featuring noninvasiveness, robustness to motion artifacts and the capacity for continuous monitoring of cerebral hemodynamic fluctuations [26], fNIRS has been extensively applied to explore the neural mechanisms underlying various sports [27]. The dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC) are identified as the core subregions of the prefrontal cortex responsible for regulating spatial cognition and motor decision-making, exhibiting task-specific activation during spatial memory processing [28–32]. Accordingly, the bilateral DLPFC and VLPFC were selected as regions of interest (ROIs) in this study to systematically dissect the neural pathways through which orienteering expertise modulates spatial cognition.

A comprehensive review of prior studies confirms the facilitative effects of aerobic and orienteering training on spatial memory, as well as the central role of the prefrontal cortex in spatial cognitive processing. However, critical research gaps still exist. Most previous work merely validates the overall improvements in spatial cognition induced by orienteering, without systematically disentangling the interactive relationships among orienteering experience, cognitive behavioral performance and dynamic prefrontal activation. Moreover, few targeted investigations have explored neural processing patterns and disparities in neural efficiency within non-specialized general cognitive contexts.

To address the aforementioned research gaps, the current study recruited orienteers with distinct levels of competitive experience, classified into an expert group and a novice group. Combining behavioral assessments with fNIRS neuroimaging, this study centers on core spatial memory indicators to explore the interactive effects of orienteering experience and prefrontal activation on cognitive performance. Two research hypotheses were proposed as follows:

(1) At the behavioral level, significant differences in task accuracy and total response time will emerge between orienteers with high and low competitive experience during the spatial memory maze task.

(2) At the neural activation level, marked disparities in oxyhemoglobin ($HbO_2$) activation intensity will be detected across prefrontal subregions between the two groups. The expert group will demonstrate superior neural efficiency, and prefrontal activation magnitudes will be significantly correlated with individual spatial memory performance.

## Materials and Methods

# Participants

A total of 40 male participants were recruited and split into an expert group and a novice group based on their orienteering training experience.

1. 1.Expert group: 20 males, mean age = 21.5 ± 2.5 years, mean training duration = 2.5 ± 0.5 years, all with abundant orienteering training and competition experience.
2. 2.Novice group: 20 males, mean age = 20.5 ± 1.5 years, with no prior orienteering training experience.

Inclusion criteria were listed as follows:

(1) Matched educational attainment across all participants;

(2) Right-handed;

(3) Normal or corrected-to-normal visual acuity;

(4) No clinical history of neurological disorders;

(5) Proficient mastery of fundamental orienteering techniques (only applicable to the expert group);

(6) No prior participation in analogous fNIRS spatial cognitive control experiments, to eliminate practice effects from repeated testing.

This study was approved by the Harbin Sport University (Ethics Approval No.: 2026104). All experimental procedures involving human participants were performed in strict accordance with the ethical principles of the Declaration of Helsinki and the relevant guidelines and regulations for human subject research.

Prior to the formal experiment, the purpose, experimental process, potential risks and benefits of the study were fully explained to all participants. Written informed consent was obtained from each participant before data collection.

## Experimental Design and Stimuli

The study employed a 2 (Group: expert group, novice group) × 3 (Cognitive Load: low, medium, high) mixed experimental design. The between-subject independent variable was orienteering expertise, and the within-subject independent variable was maze cognitive load. Dependent variables consisted of two categories: behavioral indicators (spatial judgment accuracy, total response time per trial) and neuroimaging indicators ($HbO_2$ activation magnitude of each region of interest (ROI) in bilateral prefrontal cortices). This design aimed to unpack hierarchical cognitive processing patterns and heterogeneous prefrontal hemodynamic responses of participants with different orienteering expertise under a non-specialized visuospatial paradigm.

Standardized octagonal topological maze images with graded cognitive loads served as visual experimental stimuli. Three load levels (low, medium, high) were established, with three independent maze versions prepared for each level. Every maze featured eight discrete exit/entry ports evenly distributed along its octagonal perimeter, and only one pair of unobstructed connected exits existed in each maze to avoid logical confusion caused by multiple solvable routes. All stimulus materials underwent content validity evaluation and load gradient calibration by three associate professors specializing in orienteering, to guarantee distinct load stratification and robust task validity. (This experiment has confirmed that we got informed consent from all the experts.)

During the formal testing phase, participants sat upright in front of the display monitor and were instructed to minimize head movements throughout the task to reduce noise in brain signal acquisition. Visual stimuli were delivered via PsychoPy-2025.1.1 Builder, which automatically recorded behavioral metrics including task accuracy and single-trial response latency in real time. Meanwhile, a functional near-infrared spectroscopy (fNIRS) system was used to continuously collect oxyhemoglobin ($HbO_2$) signals covering the bilateral prefrontal cortex. This experimental paradigm enables systematic exploration of the interactive relationships among athletes' orienteering expertise, spatial cognitive load, and prefrontal cortical activation patterns.

## Experimental Apparatus

Cortical hemodynamic signals were acquired using the continuous-wave fNIRS system LIGHTNIRS manufactured by Shimadzu, Japan. The sampling rate was set to 13.3 Hz. A standardized prefrontal optode cap matched to the system was equipped with eight light emitters covering three characteristic wavelengths (780 nm, 805 nm, 830 nm) and eight signal detectors. The pairing of emitters and detectors generated a total of 22 independent channels for hemodynamic measurement.

Figure 2 illustrates the channel layout of the fNIRS system and its corresponding calibrated brain regions. The left panel displays channel categorization according to four predefined regions of interest (ROIs): blue channels correspond to the ventrolateral prefrontal cortex (VLPFC), brown channels to the dorsolateral prefrontal cortex (DLPFC), green channels to the frontal pole area (FOA), and yellow channels to the orbitofrontal area (OFA). Each colored channel with a unique serial number is distinctly matched to its target subregion. The right panel presents a schematic diagram of the optode arrangement, in which red squares denote light emitters and blue squares represent signal detectors. Black connecting lines paired with numerical labels mark all 22 recording channels, explicitly demonstrating the spatial arrangement and emitter-detector pairing configuration. This standardized channel layout lays a solid methodological foundation for subsequent analyses of neural activation patterns across distinct prefrontal subregions based on alterations in oxyhemoglobin ($HbO_2$) concentration.

## Experimental Procedure

Prior to laboratory attendance, all participants were instructed to refrain from strenuous exercise, caffeine, and alcohol intake for 24 h [33], to maintain stable cerebral arousal and eliminate confounding physiological arousal effects on spatial cognitive performance [34]. Upon arrival at the laboratory, participants acclimatized to the indoor environment to stabilize their mental and physical states. Trained experimenters then delivered standardized task instructions and collected demographic and sport-specific information, including age, gender, years of training, and competitive ranking.

Subsequently, participants were fitted with the fNIRS optode cap, whose tightness was fine-tuned for proper scalp contact. Spatial calibration of all optode channels was performed following the international 10–20 electrode placement system. The optical connectivity and signal-to-noise ratio (SNR) of each individual channel were verified one by one. After quality inspection, a 30-s resting-state baseline hemodynamic time series was recorded, followed by the commencement of the formal maze cognitive task.

Controlled testing environment: Participants sat upright in front of an LCD visual display and adjusted their torso and upper limbs to a comfortable operating posture, with both hands resting on a standard response keyboard. The laboratory was maintained under standardized dim-light and low-noise conditions to block irrelevant visual and auditory external distractors.

Five orienteering athletes were recruited to complete pilot tests before formal data collection to optimize experimental parameters including task duration and stimulus presentation logic; data from pilot participants were excluded from all formal statistical analyses. Figure 3 shows photographs captured during formal experimental sessions depicting participants undertaking the maze task. All data collection procedures were conducted in the laboratory of Harbin Sport University, where behavioral data and time-series oxyhemoglobin ($HbO_2$) signals from bilateral prefrontal cortices were recorded

simultaneously. This multimodal dataset was used to characterize stratified cognitive processing patterns among participants with varying orienteering expertise.

All experimental scripts were programmed using PsychoPy-2025.1.1 Builder. As illustrated in Fig. 4, standardized task instructions were displayed in full-screen mode at the start of each block. Participants pressed the spacebar to commence the formal experiment only after fully understanding all task rules. The trial sequence followed a fixed timeline: a black central fixation cross was presented for 1 s to stabilize visual attention, followed by the octagonal maze stimulus. Participants were required to observe the maze topological layout and identify the sole pair of unobstructed connected exits. They typed the numerical labels of the two exits via the keyboard and clicked the bottom-right on-screen button to advance to the next trial. No rigid response deadline was imposed to allow sufficient time for spatial reasoning, and immediate accuracy feedback was provided after each submitted response.

## Data Collection and Statistical Analysis

# Behavioral Data

All behavioral statistical analyses were performed in SPSS 26.0. The Shapiro-Wilk test was first applied to assess data normality. Since accuracy metrics violated the normality assumption, nonparametric statistical approaches were adopted for all inferential tests. The Mann-Whitney U test was used to compare behavioral performance between the expert and novice groups at each difficulty level. The Friedman test was conducted to examine the main effect of task difficulty, with Bonferroni correction applied for post-hoc multiple comparisons. A stratified nonparametric test was utilized to evaluate the interaction between group and task difficulty [35, 36]. The significance threshold was set at $\alpha = 0.05$.

## fNIRS Data Preprocessing

Offline preprocessing of raw fNIRS recordings was completed with the manufacturer's dedicated analysis software, following four sequential procedures:

1. 1.Signal denoising: A moving average filter was implemented to eliminate high-frequency noise and motion artifacts induced by minor head movements, ambient light interference, and circuit noise from the recording apparatus.
2. 2.Baseline correction: All hemodynamic traces were normalized against the resting-state baseline signal to eliminate systematic bias originating from baseline drift.
3. 3.Channel exclusion: Invalid channels with weak signal amplitude distorted waveforms, or insufficient signal-to-noise ratio (SNR) were discarded from further analysis.
4. 4.Regional signal aggregation: Mean $HbO_2$ values across all valid channels within each predefined region of interest (ROI) were calculated to quantify the overall activation magnitude of each prefrontal subregion.

## Statistical Analyses for Neuroimaging Data

Between-group differences in $HbO_2$ activation intensity across individual prefrontal subregions were assessed via the Mann-Whitney U test. The Friedman test was adopted to detect the main effect of task difficulty on global prefrontal activation strength. The Scheirer-Ray-Hare nonparametric analysis of variance was used to test the main effects and two-way interactive effects of group, task difficulty, and brain region; Bonferroni-corrected rank-sum tests were implemented for post-hoc pairwise comparisons. Spearman's rank correlation analysis was performed to quantify linear associations between ROI $HbO_2$ activation and behavioral outcome measures. (The datasets used and analyzed in this study can be obtained upon reasonable request from the corresponding author)

## Results

# Behavioral Outcomes

The results of Shapiro-Wilk tests indicated that only the response time data of the novice group conformed to a normal distribution ($P > 0.05$). All other indicators (accuracy of both groups and response time of the expert group) deviated significantly from normality（even $P < 0.001$）. Accordingly, all subsequent statistical inferences were conducted using nonparametric tests. Detailed test statistics are presented in Table 1.

Table 1
Results of Normality Tests

| | | Kolmogorov–Smirnov Test | | | Shapiro–Wilk Test | | |
|---|---|---|---|---|---|---|---|
| Indicator | Group | Statistic | df | p | Statistic | df | p |
| Accuracy | Expert group | 0.538 | 20 | < 0.001 | 0.236 | 20 | < 0.001 |
| | Novice group | 0.319 | 20 | < 0.001 | 0.798 | 20 | < 0.001 |
| Response time | Expert group | 0.279 | 20 | < 0.001 | 0.664 | 20 | < 0.001 |
| | Novice group | 0.168 | 20 | 0.139 | 0.928 | 20 | 0.143 |

# Between-group Differences and Main Effect of Task Difficulty

Descriptive statistical trends revealed that as maze cognitive load increased progressively, spatial judgment accuracy exhibited a linear decreasing tendency, while single-trial response latency showed a linear increasing trend for both groups. Across low, medium and high difficulty conditions, the expert group consistently achieved higher accuracy and markedly shorter response latencies relative to the novice group. These hierarchical behavioral differences are illustrated in Fig. 5.

Mann-Whitney U test results demonstrated that the expert group attained significantly higher overall task accuracy (Z = 4.761, P < 0.001)and shorter total response time（Z=-3.892, P < 0.001）compared with the novice group. Separate comparisons at each difficulty level further confirmed significant intergroup discrepancies in both accuracy and response time （even P < 0.05）.

Friedman tests identified a robust main effect of task difficulty on both accuracy($\chi^2$=52.37, P < 0.001)and total response time （$\chi^2$=58.12, P < 0.001）. Post-hoc pairwise comparisons with Bonferroni correction yielded significant differences between every pair of difficulty tiers (even P < 0.01）, indicating that behavioral performance deteriorated progressively with elevated cognitive load.

Scheirer-Ray-Hare nonparametric analysis of variance revealed highly significant interaction effects between group and cognitive load for both accuracy and response time (All P < 0.01). Simple effect decomposition further verified that the magnitude of behavioral performance gaps between the two groups was substantially larger under high-load conditions than low-load conditions.

# fNIRS Imaging Results

# Global Activation Patterns of the Prefrontal Cortex

Under task-evoked conditions, broad bilateral prefrontal activation was observed in both groups, with significantly elevated oxyhemoglobin ($HbO_2$) concentrations relative to the resting baseline. Regions exhibiting the strongest activation were localized to the bilateral dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC), consistent with the canonical core brain regions subserving spatial working memory (see Fig. 6).

# Intergroup Differences in Hemodynamic Activation

Mann-Whitney U tests revealed that the expert group exhibited significantly stronger $HbO_2$ activation within bilateral DLPFC (P < 0.01)and bilateral VLPFC（P < 0.05）compared with the novice group. No statistically significant intergroup differences were detected for activation magnitudes in the frontal pole area (FOA) and orbitofrontal area (OFA) （even P > 0.05）.

# Main and Interaction Effects

Scheirer-Ray-Hare nonparametric factorial analysis of variance yielded the following statistical outcomes:

A highly significant main effect of cognitive load was identified (P < 0.001). Global prefrontal $\Delta HbO_2$ activation magnitude increased incrementally as task cognitive load rose. A highly significant main effect of region of interest (ROI) was also found across prefrontal subregions（P < 0.001）, with substantially larger hemodynamic responses detected in DLPFC and VLPFC relative to FOA and OFA.

A highly significant Group × Cognitive Load interaction was observed (P < 0.01). Simple effect decomposition demonstrated that intergroup hemodynamic disparities were only significant in DLPFC

under low cognitive load （P < 0.05）. In contrast, both DLPFC and VLPFC showed highly significant activation differences between the two groups under high cognitive load（All P < 0.01）, indicating that hemodynamic heterogeneity across individuals with varying orienteering expertise was amplified during high-demand spatial processing.

A highly significant Group × Prefrontal ROI interaction was also detected(P < 0.01). Intergroup disparities in hemodynamic activation were specifically restricted to the two core spatial cognitive subregions (DLPFC and VLPFC), whereas no group-based differentiation was evident in the frontal pole and orbitofrontal cortices.

# Correlation Analysis Between DLPFC Activation and Task Accuracy

Spearman's rank correlation analysis was performed to characterize the association between dorsolateral prefrontal cortex (DLPFC) neural activation and behavioral performance in participants with distinct orienteering expertise levels. Separate correlation tests were conducted for the expert group and novice group to examine the relationships between DLPFC oxyhemoglobin concentration changes ($\Delta HbO_2$ beta values) and maze task accuracy.

As visualized in Fig. 7, distinct correlational patterns were observed between the two groups. For expert orienteers, DLPFC activation intensity exhibited a strong significant positive correlation with task accuracy($r_s$=0.72,p < 0.001). This robust neural-behavior coupling indicates that greater neural activation within the dorsolateral prefrontal cortex corresponds to superior spatial judgment accuracy among individuals with extensive orienteering experience. In contrast, the correlation between DLPFC activation and accuracy failed to reach statistical significance in the novice group （$r_s$=0.19,p = 0.416）, with no consistent association detected.

Collectively, these findings suggest that orienteering expertise serves as a critical modulator shaping the coordinated coupling between DLPFC hemodynamic activation and cognitive behavioral performance. Experts who have undergone long-term specialized training develop well-established prefrontal circuits supporting cognitive control and behavioral execution, whereas novices have not yet formed this functional neural-behavior linkage.

## Discussion

The present study adopted a non-specialized gradient maze topological judgment paradigm combined with multimodal fNIRS cortical hemodynamic imaging to systematically disentangle hierarchical spatial cognitive performance and prefrontal hemodynamic response heterogeneity among orienteers with distinct training expertise. Cross validation of behavioral and neuroimaging multimodal results demonstrated that expert orienteers maintained stable performance advantages in general visuospatial tasks irrelevant to their specialized sport, accompanied by stronger task-specific hemodynamic

responses in core prefrontal spatial cognitive subregions. Cortical activation magnitude exhibited hierarchical coupling with spatial judgment performance, fully verifying the two primary hypotheses proposed at the outset of this research.

## Cognitive Transfer Effects Induced by Long-Term Orienteering Training

Behavioral results revealed that expert orienteers achieved higher accuracy and shorter response latencies during maze tasks, with such advantages amplified under high cognitive loads. The octagonal maze paradigm adopted in this study represented a non-specialized cognitive task fundamentally distinct from the map-reading skills required in competitive orienteering. Therefore, the observed performance gaps cannot be solely attributed to proficiency in sport-specific techniques, but rather reflect the transfer of general spatial cognitive capacity shaped by prolonged orienteering training.

From the perspective of cognitive processing mechanisms, orienteering relies on a cyclic processing chain consisting of mental map representation, map-terrain spatial matching, and dynamic route decision-making [37–39]. Long-term training repeatedly engages high-load cognitive operations including spatial coordinate transformation, topological structure identification, and multi-alternative path deliberation, effectively expanding spatial working memory capacity and improving spatial reasoning efficiency. Improvements in such high-order general spatial cognitive efficiency possess cross-scenario transferability, which explains the consistent performance edges observed during unrelated maze judgment tasks.

The significant Group × Cognitive Load interaction further supports core deductions from cognitive transfer theory. Low-load tasks impose low thresholds on spatial working memory occupancy; both groups can mobilize basic cognitive resources to complete trials, yielding minor intergroup performance gaps. In contrast, high-load mazes demand substantial working memory resources to simultaneously process multiple topological cues and execute complex path reasoning. Leveraging efficient spatial cognitive strategies cultivated through years of training, experts exhibit drastically amplified performance benefits under high demands, which aligns perfectly with classical cognitive transfer theory stating that individual disparities in cognitive capacity become more pronounced under elevated cognitive load.

## Neural Efficiency Characteristics of Prefrontal Activation

Consistent with prior neuroimaging research on spatial working memory, widespread prefrontal activation was detected across both groups during maze trials, with the most robust responses localized to the DLPFC and VLPFC. The DLPFC serves as the core regulatory subregion for spatial working memory, responsible for sustaining spatial representations and implementing cognitive control [40–41]. The VLPFC primarily mediates the encoding and retrieval of visuospatial cues; the two subregions operate synergistically to complete path identification and reasoning within maze tasks [42–44].

Between-group comparisons indicated significantly stronger $HbO_2$ activation in both the DLPFC and VLPFC among experts, paired with superior behavioral performance. This finding extends neural efficiency theory: individuals with domain expertise display intensified, concentrated activation in task-specific functional cortices and suppressed activation in irrelevant brain regions, leading to overall elevated neural processing efficiency. In this study, enhanced activation was exclusively confined to the DLPFC and VLPFC (core spatial cognitive cortices) in experts, while no intergroup differences emerged in the FOA and OFA—this pattern precisely mirrors the specialized activation signature characteristic of expert populations.

Interaction results further illustrated that intergroup DLPFC activation discrepancies were magnified under high difficulty, identifying the DLPFC as the key subregion modulated by cognitive load. Increased task difficulty elevates spatial working memory demands, requiring greater recruitment of DLPFC neural resources for regulatory processing. Years of orienteering training enhance the task responsiveness of the DLPFC in expert athletes, enabling them to mobilize additional neural resources to sustain robust cognitive performance under high load—this constitutes the neural substrate underlying their more prominent behavioral advantages in complex maze trials.

# Mechanistic Insights Into Brain-Behavior Coupling

Correlation analyses reinforced the central functional role of the DLPFC in spatial cognition. DLPFC activation intensity correlated positively with task accuracy and negatively with response latency, providing neurobiological evidence for the cognitive-enhancing effects of orienteering. Greater DLPFC hemodynamic responses predicted more accurate and faster spatial judgments, marking this subregion as a viable neural biomarker for individual spatial cognitive capacity.

Notably, VLPFC activation correlated significantly only with accuracy, with no meaningful association with response time. This dissociation arises from functional specialization across prefrontal subregions: the VLPFC predominantly participates in early visuospatial cue encoding, primarily modulating judgment precision, whereas the DLPFC governs sustained working memory maintenance and subsequent decision execution, jointly regulating both processing speed and accuracy. This functional division aligns with the subregional dissociation theory of the prefrontal cortex.

# Study Limitations and Future Research Directions

This study contains four key limitations:

First, the cross-sectional design can only identify correlational relationships between orienteering experience and cognitive ability, rather than establish causal effects. Longitudinal intervention trials should be conducted in subsequent research to validate the causal promotional effects of systematic orienteering training on cognitive function and prefrontal neural activity.

Second, only male participants were recruited, ignoring potential gender disparities in spatial cognition and cortical hemodynamic activation. Future investigations should expand the sample pool to include

female orienteers for comparative analysis.

Third, fNIRS is limited to measuring hemodynamic fluctuations within the prefrontal cortex and cannot capture activity in subcortical structures such as the hippocampus and parietal lobe, despite spatial cognition relying on whole-brain network coordination. Combined fMRI-fNIRS protocols can be adopted in follow-up work to unpack full-brain network mechanisms supporting spatial navigation and reasoning.

Fourth, although maze stimuli improved ecological validity, they remain simplified abstractions of real-world outdoor orienteering terrain. Virtual reality (VR) technology can be utilized in future research to construct immersive navigation scenarios and boost the external validity of experimental findings.

## Conclusions

Using nonparametric statistical approaches, the present study systematically investigated the modulatory effects of orienteering experience on spatial cognition from both behavioral and neural perspectives. The main conclusions are summarized as follows:

1. 1.Long-term specialized orienteering training induces transfer benefits in general spatial cognitive ability. Expert orienteers achieve higher judgment accuracy and faster processing speed during the non-specialized maze task, and such performance advantages are amplified under high cognitive load.
2. 2.Orienteering training optimizes prefrontal activation patterns. Expert athletes exhibit stronger and more functionally specific hemodynamic activation in the dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC), demonstrating expert-specific neural efficiency profiles.
3. 3.Activation intensity of the DLPFC is closely associated with spatial cognitive performance, serving as a core neural biomarker for predicting individual spatial cognitive capacity.

This study provides novel empirical evidence for theories regarding exercise-facilitated cognitive development and offers neuroscientific support for improving spatial cognitive ability via orienteering training.

## Declarations

# Author Contribution

J.Z. and Y.L. Wrote the main manuscript text and experimental procedures, B.Q.Prepared Figures 1-7 and provided guidance and supervision for the experiment Y.G.Prepared Table 1 and went along with the experiment process. All the authors have reviewed the manuscript.

# Data Availability

The datasets generated and analyzed in this study include functional near-infrared spectroscopy brain imaging data, maze task behavioral data, and demographic baseline data of human participants. Due to the inclusion of personal privacy and ethical information related to participants, these datasets cannot be publicly deposited in open-access repositories. All de-identified research data are available from the corresponding author upon reasonable academic request and compliance with relevant ethical regulations.

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# Figures

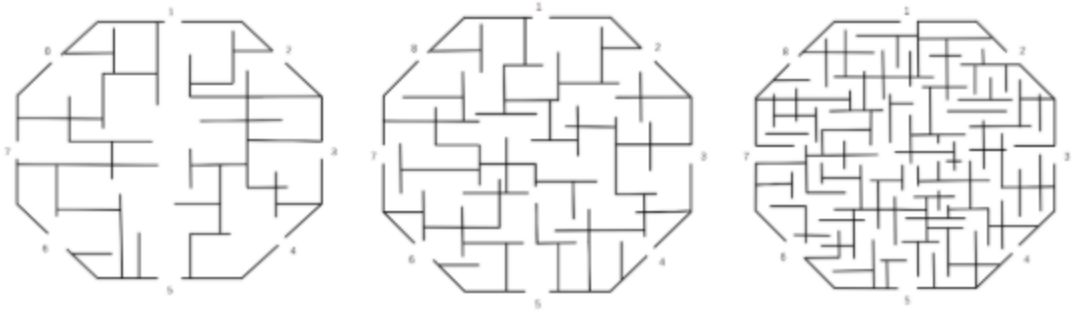


**Figure 1**

Representative examples of maze stimuli at low, medium, and high difficulty levels.

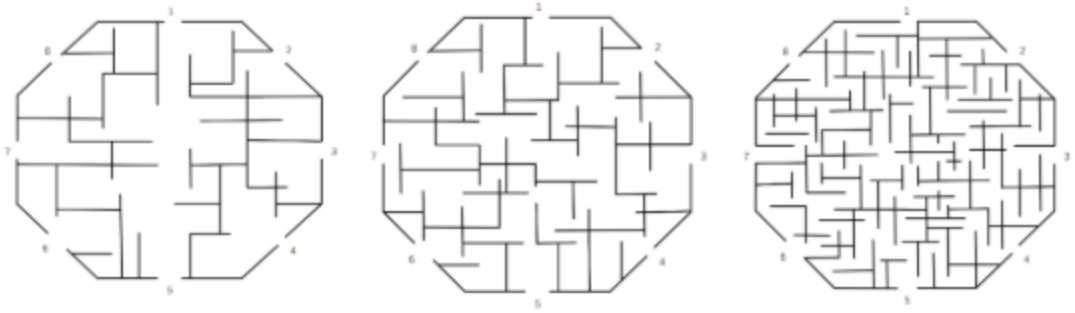


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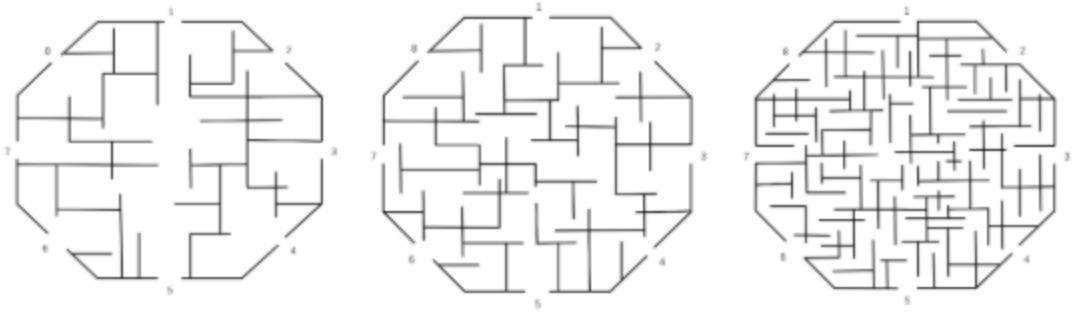


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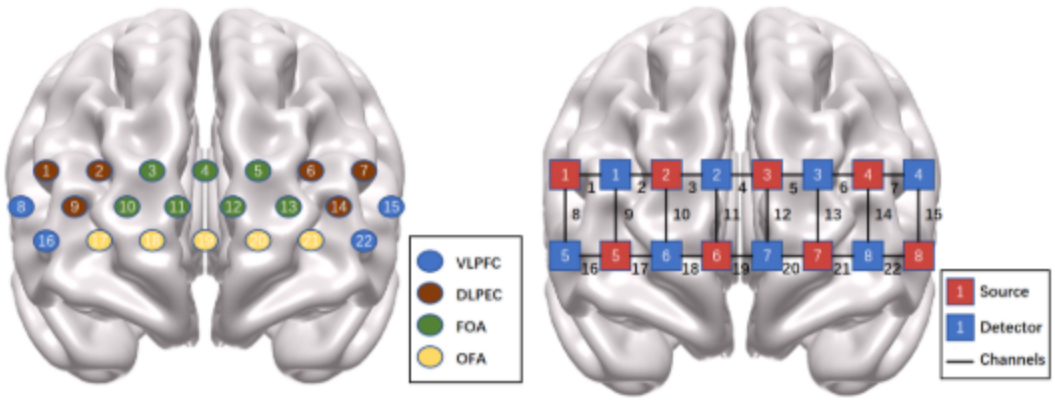



**Figure 2**

Representative examples of maze stimuli at low, medium, and high difficulty levels.

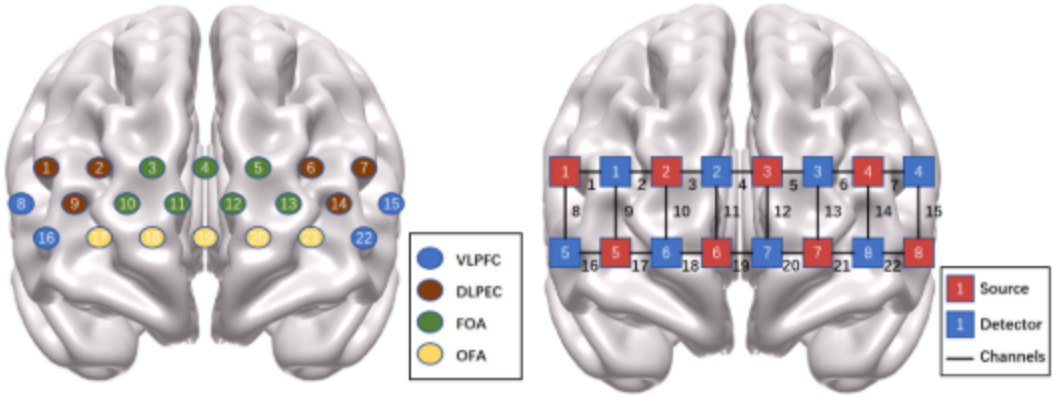



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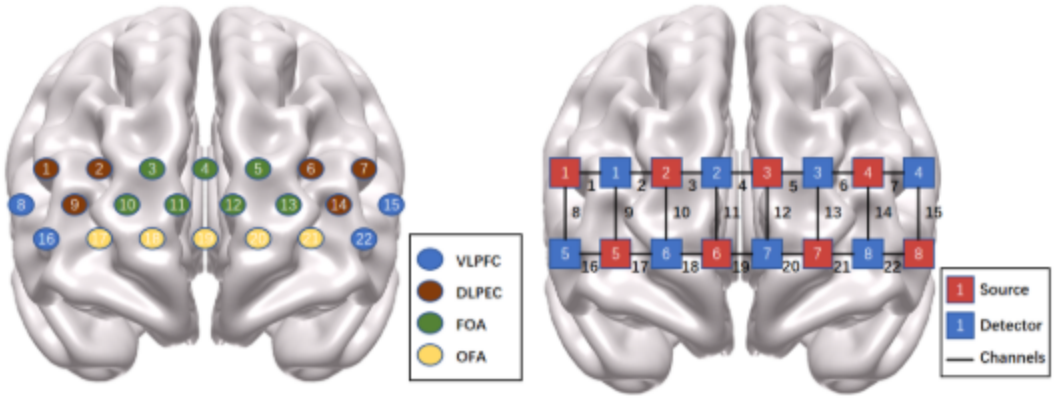



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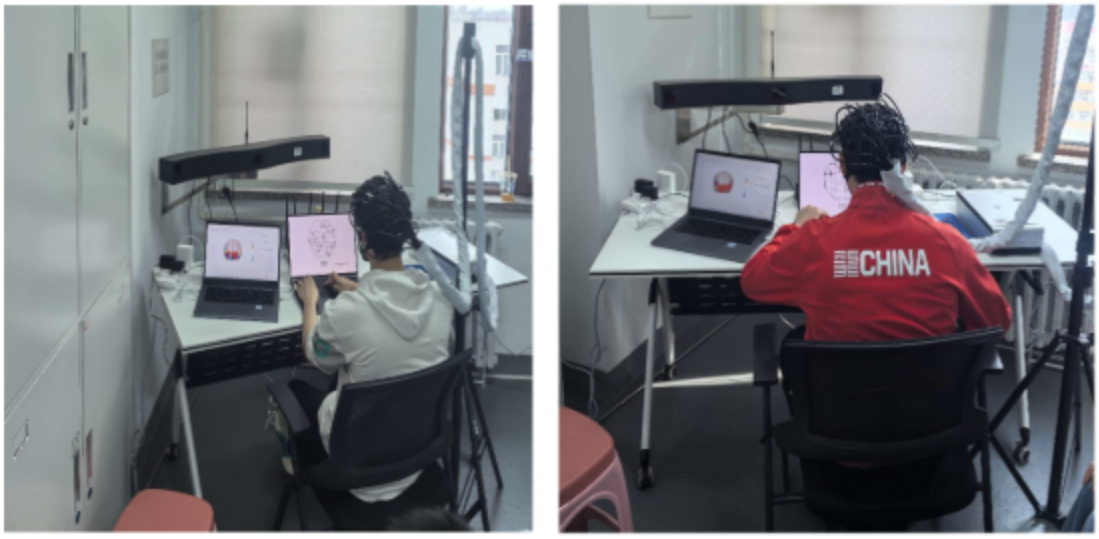



**Figure 3**

Photograph of an experimental session during fNIRS data collection.

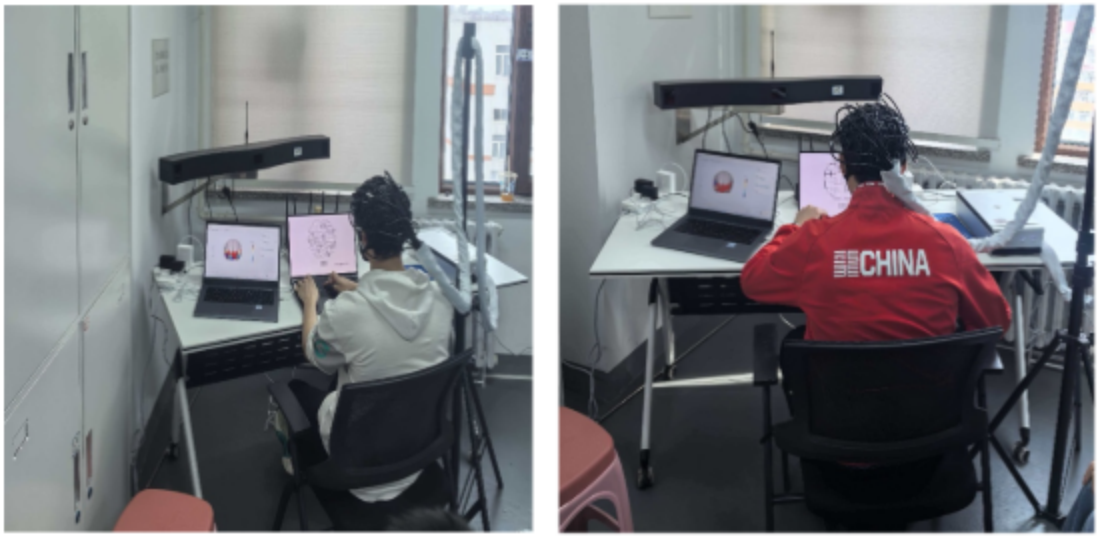



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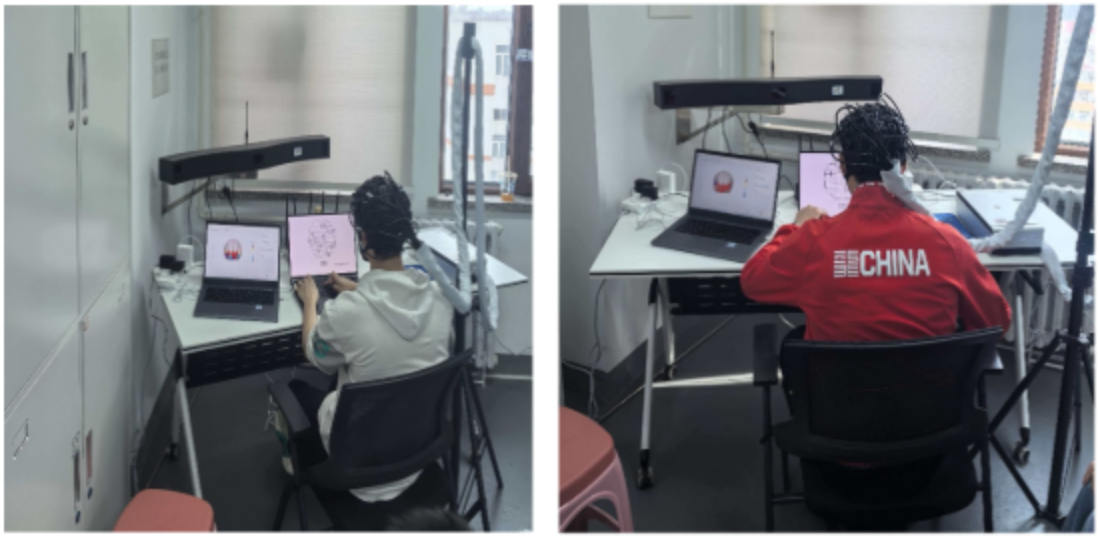



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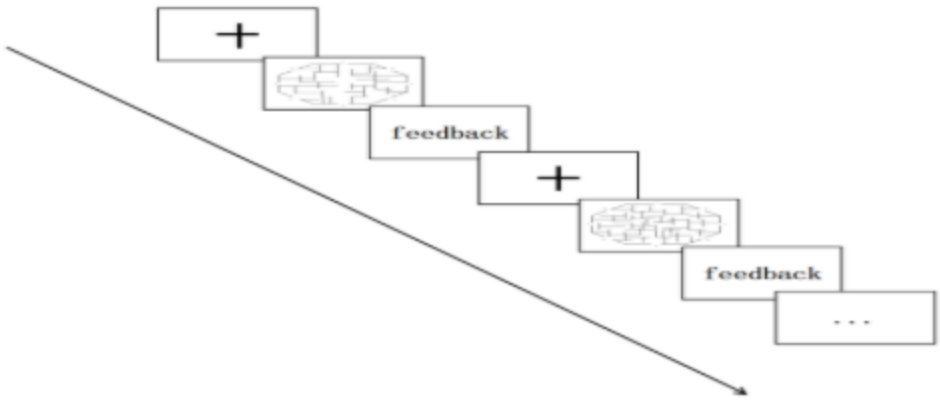



**Figure 4**

Schematic diagram of the experimental procedure.

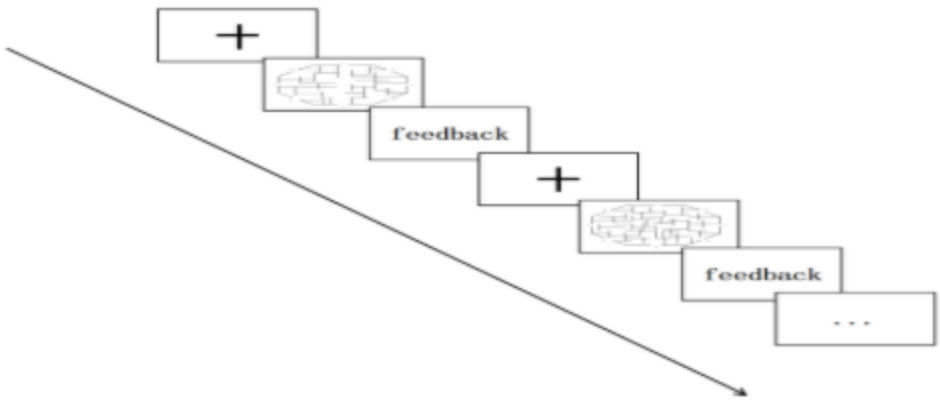



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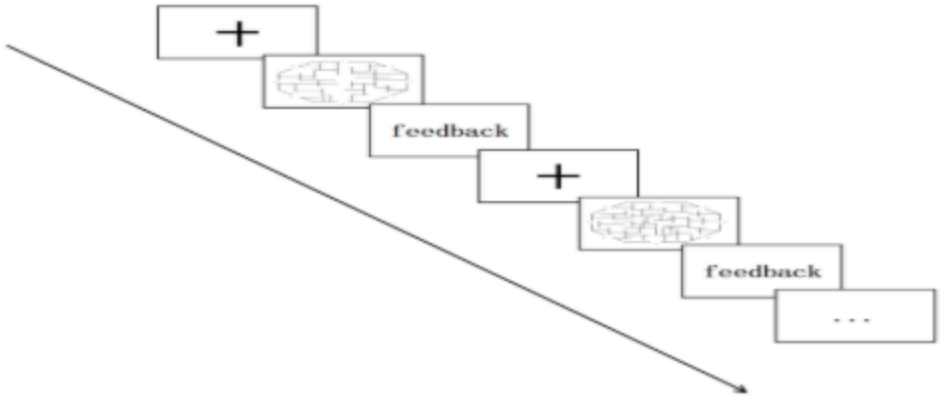



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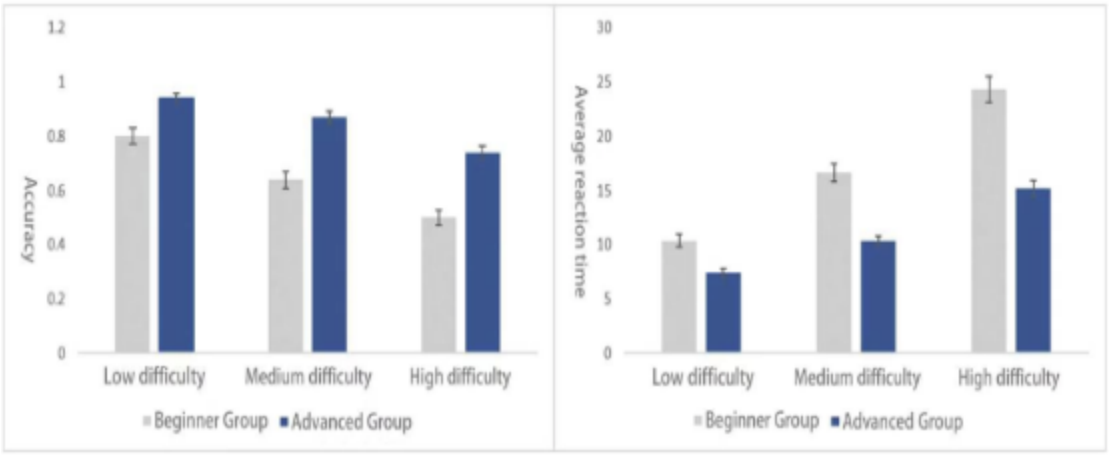



**Figure 5**

Accuracy and mean response time of two groups under three difficulty levels.(Error bars denote SEM)

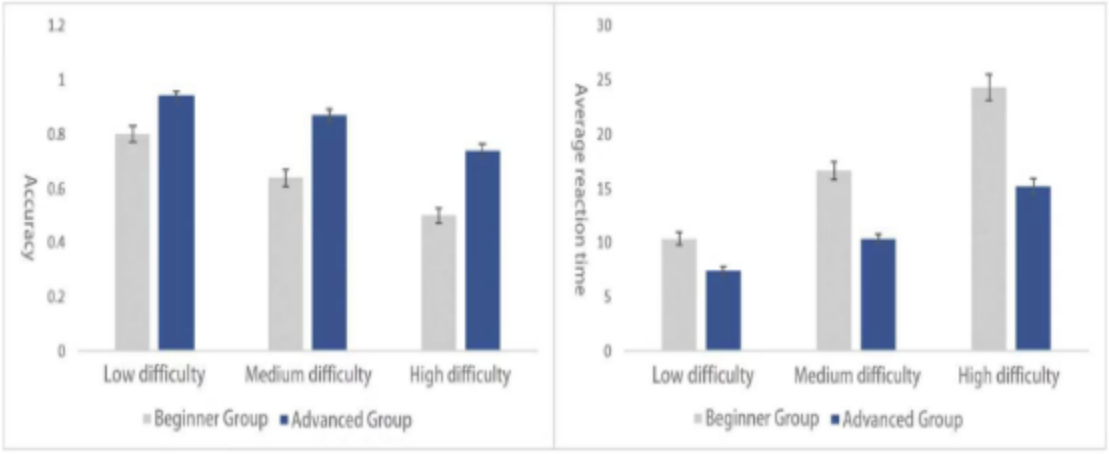



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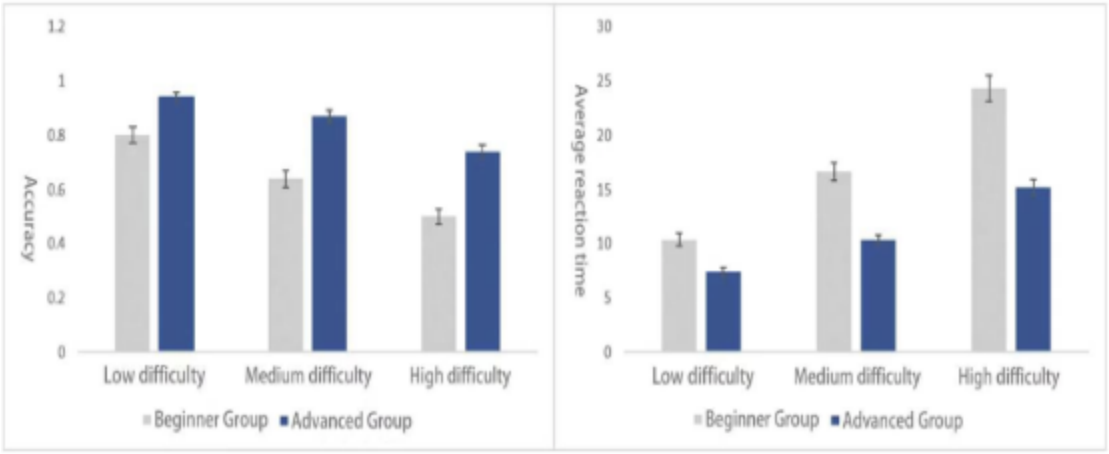



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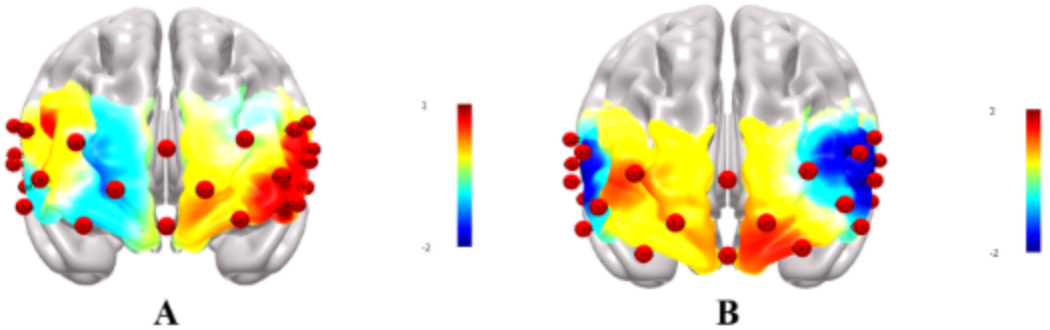



**Figure 6**

Prefrontal $HbO_2$ activation heatmaps under task state. (A) Novice group, (B) Expert group.

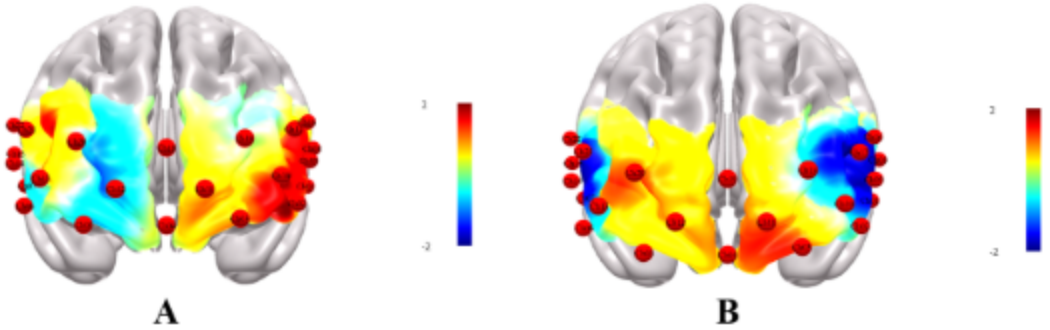



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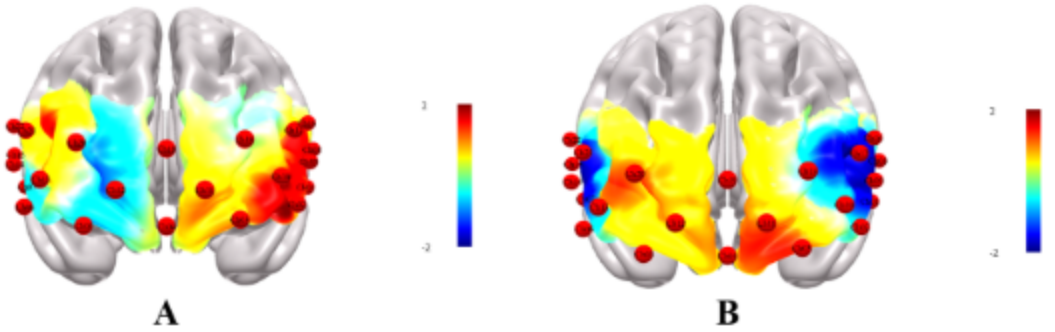



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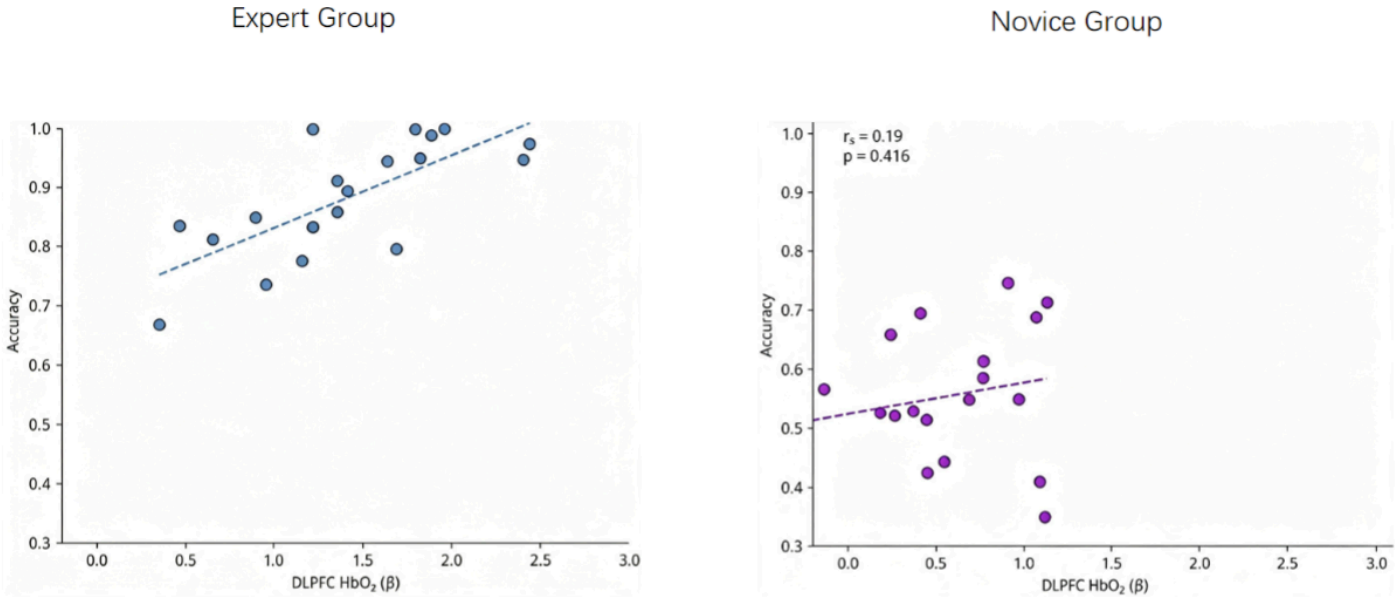



**Figure 7**

Spearman correlations between DLPFC hemodynamic activation and task accuracy for expert and novice orienteers. Note: Left: Expert Group; Right: Novice Group. DLPFC $HbO_2$(β) = beta estimates of oxyhemoglobin concentration changes in the dorsolateral prefrontal cortex. r, Spearman's rank correlation coefficient; p, significance value.

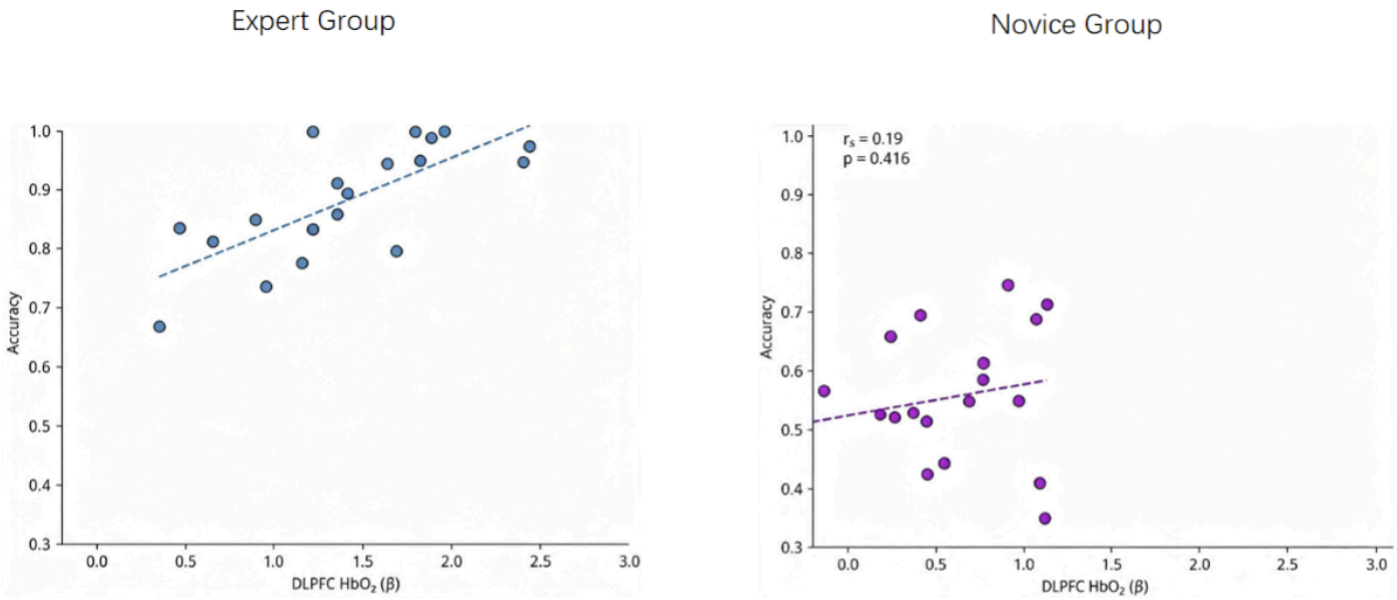



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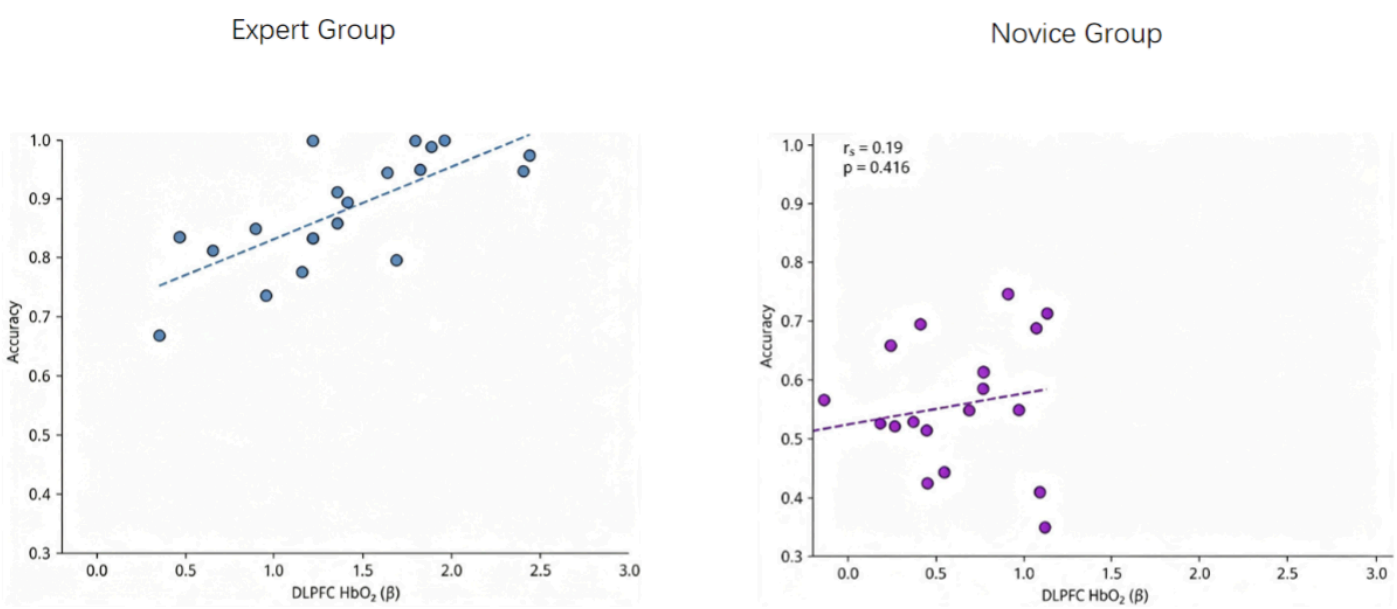



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