VR Motor-Cognitive Dual-Task Training Effects on Spatial Visualization Ability in Individuals with Low Spatial Ability: Evidence from Behavior and fNIRS

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Date: 2026-04-29T03:25:29+00:00

Abstract

Spatial visualization ability is a core component of spatial cognition. Compared with traditional cognitive training, a new intervention approach that integrates physical activity and cognitive processing provides a new direction for enhancing this ability, particularly for improving deficits in individuals with low spatial ability; however, its effectiveness still requires empirical evidence from behavioral and neural levels. This study aims to explore the promotional effects and neural plasticity mechanisms of Virtual Reality (VR) motor-cognitive dual-task training on the spatial visualization ability of individuals with low spatial ability. 120 college students with low spatial ability were screened and randomly assigned to a VR motor-cognitive dual-task group, a VR motor group, a VR cognitive group, and a control group for an 8-week intervention. Spatial visualization tasks were used to evaluate behavioral performance, and Functional Near-Infrared Spectroscopy (fNIRS) was utilized to record changes in prefrontal-parietal network activation before and after the intervention. Furthermore, a random forest machine learning model was employed to analyze the discriminative features of neural patterns. The results indicated that the VR motor-cognitive dual-task group significantly outperformed the other groups in both spatial visualization behavioral performance and neural efficiency, manifested by a significant decrease in activation levels in the Left Frontopolar Area (L-FPA) and the Right Primary Motor Cortex (R-M1), suggesting an optimization of neural efficiency in cognitive processing. The machine learning model further verified that the neural activity patterns of the dual-task group were highly separable from those of the control group, with the change in activity in R-M1 and L-FPA being the most discriminative features. VR motor-cognitive dual-task training can significantly enhance the spatial visualization ability of individuals with low spatial ability by synergistically optimizing the neural efficiency of the prefrontal and motor cortices. This study provides multimodal evidence for the "body-cognition integration" theory and establishes a methodological foundation for precision intervention paradigms based on neuro-markers.

Full Text

Preamble

The Impact of VR Motor-Cognitive Dual-Task Training on Spatial Visualization Ability in Individuals with Low Spatial Ability: Evidence from Behavior and fNIRS

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Abstract

Spatial visualization ability is a core component of spatial intelligence, playing a crucial role in daily life, academic achievement, and professional performance. However, individuals with low spatial ability often face significant challenges in complex spatial tasks. This study investigates the impact of Virtual Reality (VR) motor-cognitive dual-task training on the spatial visualization abilities of individuals with low spatial ability, utilizing both behavioral measures and functional Near-Infrared Spectroscopy (fNIRS). By integrating physical activity with cognitive challenges in an immersive VR environment, we aim to explore the neural mechanisms underlying spatial ability enhancement and provide empirical evidence for the effectiveness of dual-task interventions.

Introduction

Spatial ability refers to the capacity to generate, retain, retrieve, and transform well-structured visual images. Among its various sub-domains, spatial visualization—the ability to mentally manipulate complex spatial information—is particularly vital for success in Science, Technology, Engineering, and Mathematics (STEM) fields. Despite its importance, there is significant individual variation in spatial ability. Research has shown that spatial ability is not fixed but can be improved through targeted training.

Traditional training methods often focus on static paper-and-pencil tasks or simple computerized exercises. However, recent advancements in Virtual Reality (VR) technology offer new possibilities for more ecological and engaging interventions. VR provides an immersive 3D environment that requires users to engage in both physical movement and cognitive processing, mimicking the demands of real-world spatial navigation. Motor-cognitive dual-task training, which involves performing a physical task and a cognitive task simultaneously, has been shown to elicit greater neuroplasticity than single-task training.

Despite the potential of VR dual-task training, its specific effects on individuals with low spatial ability remain under-explored. Furthermore, the underlying cortical activation patterns during such training are not fully understood. This study employs fNIRS to monitor hemodynamic responses in the prefrontal cortex (PFC) and parietal lobe—areas closely associated with spatial processing and executive function—to elucidate the neural changes associated with spatial visualization improvements.

Methods

Participants

Participants were recruited from a university population and screened using standard spatial ability tests (e.g., the Mental Rotation Test).

Abstract

Spatial visualization ability is a core component of spatial cognition. Compared to traditional cognitive training, novel intervention approaches that integrate physical activity with cognitive processing offer a new direction for enhancing this ability, particularly for addressing deficits in individuals with low spatial ability. However, the effectiveness of such interventions requires further empirical support from both behavioral and neurological perspectives.

This study aims to investigate the promotional effects and neuroplasticity mechanisms of Virtual Reality (VR) motor-cognitive dual-task training on the spatial visualization abilities of individuals with low spatial ability.

A total of 120 college students with low spatial ability were screened and randomly assigned to a VR motor-cognitive dual-task group, a VR motor group, a VR cognitive group, or a control group for an 8-week intervention. Behavioral performance was assessed using spatial visualization tasks, while functional Near-Infrared Spectroscopy (fNIRS) was utilized to record changes in activation within the prefrontal-parietal network before and after the intervention. Furthermore, a random forest machine learning model was employed to analyze the discriminative features of neural patterns. The results indicated that the VR motor-cognitive dual-task group significantly outperformed the other groups in both behavioral performance and neural efficiency. This was evidenced by a significant reduction in activation levels in the left frontopolar area (L-FPA) and the right primary motor cortex (R-M1), suggesting an optimization of neural efficiency during cognitive processing. The machine learning model further verified that the neural activity patterns of the dual-task group were highly distinguishable from those of the control group, with the magnitude of change in R-M1 and L-FPA activity serving as the most discriminative features. VR motor-cognitive dual-task training can significantly enhance the spatial visualization ability of individuals with low spatial ability by synergistically optimizing the neural efficiency of the prefrontal and motor cortices. This study provides multimodal evidence for the theory of "body-cognition integration" and establishes a methodological foundation for precision intervention paradigms based on neuro-biomarkers.

Keywords

Virtual reality (VR), motor-cognitive dual-task training, low spatial ability, spatial visualization, fNIRS, machine learning. Classification Code: B842.1

1. Introduction

Spatial ability is a core component of human intelligence, playing a critical role in daily navigation, professional expertise in STEM fields, and overall cognitive health. Among the various dimensions of spatial ability, spatial visualization—the ability to mentally manipulate, rotate, and transform complex visual stimuli—is particularly vital. However, significant individual differences exist, and individuals with low spatial ability often face challenges in tasks requiring mental rotation and spatial orientation. Recent research has increasingly focused on whether targeted interventions, particularly those involving motor-cognitive dual-task training, can effectively enhance these abilities.

Virtual Reality (VR) technology provides a unique platform for such interventions by offering immersive, three-dimensional, and interactive environments that simulate real-world spatial challenges. By integrating physical movement with cognitive tasks, VR-based motor-cognitive dual-task training may engage neural plasticity more effectively than traditional sedentary cognitive training. Despite the potential of these interventions, the underlying neural mechanisms and the predictability of training outcomes remain insufficiently understood.

This study utilizes functional Near-Infrared Spectroscopy (fNIRS) to monitor cortical activation patterns during spatial visualization tasks. By combining neuroimaging data with machine learning algorithms, we aim to investigate the efficacy of VR motor-cognitive dual-task training for individuals with low spatial ability and to develop predictive models for identifying training responsiveness.

2. Methods

2.1 Participants

Participants were recruited based on their scores on standardized spatial ability tests (e.g., the Mental Rotation Test and the Paper Folding Test). Individuals scoring in the bottom 30th percentile were categorized as having low spatial ability and were invited to participate in the intervention.

2.2 Experimental Design and VR Training

The study employed a pre-test/post-test design with an experimental group and a control group. The experimental group underwent a multi-session VR motor-cognitive dual-task training program. This program required participants to navigate a virtual environment while simultaneously performing mental rotation and spatial memory tasks. The control group engaged in passive VR experiences without the dual-task cognitive load.

[Figure 1: see original paper]

2.3 fNIRS Data Acquisition

Cortical hemodynamic responses, specifically changes in oxygenated hemoglobin (ΔHbO_2) and deoxygenated hemoglobin (ΔHb), were recorded using a portable fNIRS system.

1 Introduction

Spatial Visualization Ability (SVA) is a core component of spatial cognition, referring to the cognitive process by which individuals represent, manipulate, and predict the dynamic changes of spatial information at a mental level. This ability is primarily manifested in the mental imagery of spatial transformations, such as the rotation or folding of objects [?]. Unlike spatial representation, which focuses on static encoding, spatial visualization emphasizes the active manipulation and optimization of spatial imagery. Deficits in this ability can lead directly to practical difficulties, such as blurred directional judgment in unfamiliar environments and low efficiency in mental rotation [?].

In everyday life, many individuals frequently describe themselves as having a “poor sense of direction,” characterized by a tendency to get lost in unfamiliar settings and difficulty in forming effective mental maps. This phenomenon is a typical manifestation of weak spatial visualization ability [?]. With the advancement of artificial intelligence and smart navigation devices becoming increasingly ubiquitous, individuals are becoming more reliant on electronic navigation. This trend may, to some extent, impair the natural development of autonomous spatial orientation and directional judgment [?]. Furthermore, the sedentary lifestyles and lack of outdoor activities prevalent in modern society have further restricted opportunities for the natural exercise of spatial cognitive abilities. Consequently, there is a rising trend in the proportion of individuals characterized by low spatial ability [?].

When performing spatial tasks, individuals with low spatial ability often require more working memory resources, leading to a significant decrease in information processing efficiency [?]. Simultaneously, these individuals typically exhibit weaker memory for environmental layouts, struggling to accurately recall the sequence of landmarks or pinpoint their own location on a map, which makes them more prone to getting lost in unfamiliar environments [?]. From the perspectives of practical cognitive demands and skill training, systematically focusing on and enhancing the spatial visualization capabilities of low-spatial-ability individuals holds significant cognitive theoretical value. Moreover, such efforts offer positive practical implications for both educational practices and daily life applications.

Cognitive neuroscience and sports psychology research have confirmed that physical activity and cognitive training exert a positive promoting effect on spatial visualization abilities. Regarding physical activity, aerobic exercises—such as running and ball games—can enhance spatial information processing efficiency by improving brain functional connectivity and neuroplasticity [?]. For instance, dynamic scanning and tactical coordination in soccer are conducive to improving an individual' s spatial perception [?], while diving strengthens spatial localization capabilities through precise body posture control in mid-air [?].

In terms of cognitive training, tasks such as map recognition, path integration, and spatial reasoning can directly improve an individual' s ability to mentally represent and manipulate spatial relationships [?, ?]. For example, map-reading training in orienteering—which involves targeted exercises like map-to-terrain matching and reference frame transformation—can effectively enhance a practitioner' s spatial working memory and mental rotation performance [?, ?].

However, most current intervention programs tend to implement physical activity and spatial cognitive training in isolation. These approaches fail to fully exploit the synergistic potential of temporal synchronicity and "motor-cognitive" coupling, thereby limiting the overall improvement of spatial visualization abilities. Existing research indicates that for patients with cognitive impairment, a combined intervention model—performing aerobic exercise followed by cognitive training—is significantly more effective than single-mode training [?]. This suggests that the integration of movement and cognition may offer superior benefits.

There may be a synergistic gain in the temporal integration of "motor-cognitive" processes. However, this sequential superposition model still struggles to simulate the real-time interaction and deep integration characteristics that emerge when physical movement and cognitive processing occur simultaneously in real-world scenarios. As the theory of embodied cognition continues to deepen and evolve, academia has increasingly emphasized the core role of the dynamic coupling between "body, environment, and cognition" in shaping cognitive processes [?]. From the perspective of this theory, interactive training models that synchronize physical movement and cognitive tasks demonstrate significant advantages, as they closely align with the contexts in which spatial abilities are utilized in the real world [?].

Taking orienteering as a primary example, this sport requires participants to simultaneously perform map recognition, path planning, and real-time decision-making while physically moving through an environment [?]. This process achieves an organic integration of motor execution and spatial cognition. Practical evidence suggests that orienteering training can effectively enhance a practitioner' s ability to determine orientation and navigate within real-world settings. This integrated approach to dual-task processing facilitates the integration of multisensory information and promotes the updating of spatial working memory. Furthermore, through the synergistic effects of physical activity and cognitive challenges, it enhances functional connectivity and neural efficiency within brain networks [?]. However, while "motor-cognitive" integrated training has demonstrated significant efficacy in real-world activities such as orienteering, its widespread promotion and application still face constraints related to venue availability and safety concerns.

The maturation of virtual reality (VR) technology provides critical methodological support for overcoming this bottleneck. VR not only enables the construction of highly realistic, immersive environments but also offers a controlled laboratory platform for research [?, ?]. From the perspective of embodied cognition theory, the advantage of Virtual Reality (VR) lies in its ability to integrate multi-sensory information with physical movement and interaction. By anchoring the cognitive process within the "bodily" experience of a virtual environment, VR strengthens the embodied construction of spatial knowledge [?]. Beyond this theoretical framework, VR technology has been extensively validated across multiple disciplines as a significant means of enhancing cognitive abilities. For instance, research by [?] demonstrates that combining brain stimulation targeting key spatial cognition regions with VR navigation training can effectively enhance activity within the core brain networks associated with spatial memory.

In the field of clinical medicine, VR serves not only as a sensitive tool for the early identification of cognitive impairment but also as an effective platform for rehabilitation training in spatial memory and path planning due to its immersive environments [?, ?]. Furthermore, in professional fields such as architectural design, VR has profoundly altered how individuals perceive and make decisions regarding spatial proportions, scales, and materials by constructing full-scale, interactive environments. This systematically improves three-dimensional thinking and spatial understanding [?]. Collectively, this evidence suggests that by providing ecological and targetable immersive experiences, VR is becoming a key technology for enhancing spatial cognition across basic research, clinical applications, and professional training.

The continuous development of functional Near-Infrared Spectroscopy (fNIRS) technology provides unique advantages for the non-invasive, real-time monitoring of cortical hemodynamic changes in naturalistic settings. This offers critical technical support for the present study' s in-depth exploration of the mechanisms underlying the benefits of synchronous "motor-cognitive" training. Because fNIRS possesses high motion tolerance, it can effectively capture the brain activation patterns presented by individuals while they perform cognitive tasks synchronized with physical activity [?]. Consequently, it is well-suited for investigating physical-cognitive coordination within VR environments.

Although this technology has limited capability for probing deep brain structures and possesses relatively low spatial resolution [?], the present study has fully accounted for these factors in both experimental design and data processing.

We strive to obtain valid brain activity data within these technical boundaries to provide a reasonable explanation for the neural mechanisms underlying training benefits. At the neural level, the prefrontal cortex plays a central role in cognitive control, working memory updating, and complex decision-making [?].

For example, in tasks involving map recognition and route selection, activation levels within these regions increase in correlation with task difficulty [?]. The parietal lobe serves as a critical hub for spatial information processing; it is responsible for integrating multimodal inputs, such as visual and proprioceptive data, to construct spatial representations. Furthermore, it supports the transformation between egocentric and allocentric reference frames [?]. In dual-task paradigms involving both physical movement and cognitive judgment, the functional coupling strength of the prefrontal-parietal network can effectively predict the quality of individual spatial task performance [?, ?].

Based on the aforementioned background, this study independently developed a multi-scenario VR motor-cognitive dual-task training program grounded in the theory of embodied cognition. The primary objective is to systematically investigate the effectiveness of this training program in enhancing the spatial visualization abilities of individuals with low spatial ability, while utilizing functional Near-Infrared Spectroscopy (fNIRS) to reveal the underlying mechanisms of brain neural plasticity. This research focuses on addressing the following scientific questions:

(1) Can VR motor-cognitive dual-task training effectively improve the spatial visualization abilities of individuals with low spatial ability?

(2) Does the motor-cognitive interactive training demonstrate superior improvement benefits compared to single motor training or single cognitive training?

(3) Does effective intervention induce unique neural activity patterns that can be captured by machine learning models, allowing the intervention group to be distinguished from the control group with high precision? Furthermore, what are the key neurobiological biomarkers associated with these changes?

2.1 Participants

An a priori power analysis was conducted using G*Power 3.1 software [?] to estimate the required sample size. With the significance level set at $\alpha = 0.05$, statistical power $(1 - \beta)$ at 0.80, and a medium effect size ($f = 0.35$), the calculation indicated a total required sample size of 94 participants, with at least 24 participants per group. To account for potential attrition and ensure statistical requirements were met, the Santa Barbara Sense of Direction Scale (SBSOD) was administered to freshman and sophomore students at a university. A total of 120 individuals with low spatial ability (60 males, 60 females) were recruited. Participants were randomly assigned to one of four experimental groups: the VR motor-cognitive dual-task group, the VR motor group, the VR cognitive group, and the control group, with 30 participants in each. Inclusion criteria were: 1) Body Mass Index (BMI) within the normal range (18.5 ~ 23.9 kg/m^2); 2) no history of traumatic brain injury or psychiatric disorders; 3) normal or corrected-to-normal vision; 4) no prior experience in orienteering or related competitions; 5) no habit of using cardinal directions (North, South, East, West) for wayfinding or giving directions; 6) no history of 3D motion sickness; 7) right-handedness; and 8) familiarity with computer keyboard layouts and no prior participation in similar experiments.

Exclusion criteria included: 1) diagnosis of psychiatric disorders such as depression or schizophrenia; 2) severe systemic diseases affecting cardiac, hepatic, or renal function; and 3) vestibular dysfunction or physical conditions that impair motor execution. Before the experiment commenced, all participants provided written informed consent and committed to refraining from additional systematic motor skill learning while maintaining their existing physical exercise habits to prevent confounding effects on neural and behavioral outcomes. This study protocol was approved by the Ethics Committee of Shaanxi Normal University (Approval No.: 202410006).

2.2.1 Spatial Ability Self-Assessment Scale

Participants were screened using the Chinese version of the Santa Barbara Sense of Direction (SBSOD) scale, as revised by [?]. This scale consists of 15 items rated on a 7-point Likert scale, ranging from "1" (strongly disagree) to "7" (strongly agree). Specifically, items 1, 3, 4, 5, 7, 9, and 14 are scored positively, while items 2, 6, 8, 10, 11, 12, 13, and 15 are reverse-scored. The final score is determined by calculating the mean of all items; individuals with a mean score below 3 are classified as having low spatial ability. In the current study, the scale demonstrated good reliability with a Cronbach' s α coefficient of 0.88.

2.2.2 VR Motor Scenario Development and Experimental Tasks

To precisely examine the mechanisms by which "motor-cognitive" synchronous training influences spatial visualization capabilities, this study developed a multimodal VR training system using the Unity engine. The system comprises three distinct experimental conditions: a VR motor-cognitive dual-task scenario, a VR motor-only scenario, and a VR cognitive-only scenario. This design allows for the precise control of intervention components and facilitates a rigorous comparative analysis.

The system features two high-fidelity virtual environments—a campus and a park—integrating geographical elements such as roads, buildings, and navigation interfaces. A total of 32 training paths were preset (16 per environment), with each path containing eight target points embedded with 3D point flags to serve as carriers for spatial navigation tasks. To achieve high-precision coupling between physical movement and virtual navigation, the system innovatively incorporates the Natural Locomotion positioning scheme. By attaching trackers to the participants' feet, the system captures the frequency, amplitude, and plantar inclination of jogging-in-place movements to drive the virtual character' s 1:1 spatial displacement in real-time. This mapping relationship underwent a two-stage calibration process—static calibration and dynamic verification—prior to the experiment to ensure that virtual movement remained synchronized with the individual' s actual physical rhythm, thereby effectively enhancing the ecological validity of physical engagement.

The three experimental task scenarios are designed as follows: 1) VR Motor-Cognitive Dual-Task Scenario: Participants must independently plan their routes using a virtual map and compass, driving the virtual character to target points via jogging-in-place to complete "check-ins." 2) VR Motor Scenario: Participants jog along a navigation line rendered on the ground, requiring no active path planning. 3) VR Cognitive Scenario: The task content is identical to the motor-cognitive scenario, but character movement is controlled via a handheld controller, involving no physical activity.

During the system development process, six active athletes from the Shaanxi Provincial Orienteering Team were invited to participate in multiple rounds of scenario testing and interaction debugging. Their feedback was used to further optimize the scene layout, task logic, and the authenticity of the motion mapping. Upon completion of each task, the system automatically exports behavioral metrics—including map usage duration, compass invocation frequency, and check-in success rates—to provide data support for subsequent analysis.

2.3 Experimental Design

This study employs a 2 × 4 mixed-factorial experimental design. The factors include Time (two levels: pre-intervention and post-intervention) and Group (four levels: VR motor-cognitive dual-task group, VR motor group, VR cognitive group, and a control group). The dependent variables consist of scores from the Santa Barbara Sense of Direction (SBSOD) scale, reaction times (MRT-RT) and accuracy rates (MRT-ACC) from the Mental Rotation Task, and brain activation levels within specific Regions of Interest (ROI) in the prefrontal and parietal lobes.

2.4.1 Overall Procedure

The experimental procedure primarily consists of four phases: the practice phase, pre-test, intervention phase, and post-test.

1. Practice Phase

The experimenter first demonstrated the operation of the VR equipment. Subsequently, each participant was guided through hands-on practice sessions to ensure that their operational proficiency reached a uniform standard across the sample.

2. Pre-test

Upon arrival at the laboratory, participants were briefed on the experimental procedure and signed informed consent forms. They then provided basic demographic information and were fitted with heart rate monitors. After sitting quietly for 15 minutes, their resting heart rate was recorded. Following this, participants were fitted with functional Near-Infrared Spectroscopy (fNIRS) devices to conduct a baseline assessment of their spatial visualization abilities.

3. Exercise Intervention

The intervention lasted for 8 weeks, with sessions occurring three times per week. Each session lasted 60 minutes and included both warm-up and cool-down activities. For both the VR motor-cognitive dual-task group and the VR motor group, exercise intensity was maintained at a moderate level, defined as 64% to 76% of the maximum heart rate (HR_{max}) [**?**]. During exercise, heart rate monitors provided real-time tracking, and participants received voice prompts to adjust their pace to remain within the target intensity range. The VR cognitive group performed the same navigational cognitive tasks using a controller without physical exercise. The control group did not participate in any organized physical exercise during the intervention period.

4. Post-test

Following the completion of the full intervention, a post-test of the mental rotation task was administered once the participants' heart rates had returned to levels near their pre-test resting heart rate. Participants received compensation upon the completion of the testing.

2.4.2 Spatial Visualization Ability Test

The test program was developed using E-prime 3.0. The task stimuli utilized the Mental Rotation Task (MRT), a classic paradigm for assessing spatial visualization ability [**?**, **?**]. At the beginning of the formal testing session, participants rested with their eyes closed for 3 minutes, during which functional Near-Infrared Spectroscopy (fNIRS) was used to collect resting-state cerebral blood flow signals to serve as a baseline. When the task commenced, a red "+" fixation point was first presented on the screen for 1 second, followed by a stimulus image displayed for 6 seconds. Each image contained the same figure at different rotation angles—specifically 0°, 60°, 120°, 180°, 240°, and 300°—alongside one distractor figure.

These six rotation angles were presented in a randomized order, with the presentation sequence counterbalanced across trials. Participants were required to identify the location of the distractor figure and respond by pressing the corresponding numeric keys: 1 for top-left, 2 for top-right, 3 for bottom-left, and 4 for bottom-right. During the practice phase, participants received feedback on their reaction time (MRT-RT) and accuracy (MRT-ACC) after each trial; however, no feedback was provided during the formal testing phase. The entire test consisted of 6 blocks, with each block comprising 8 trials, totaling 48 trials. A 30-second rest period was provided between blocks, and the order of blocks was randomized. The total duration of the test was approximately 15 minutes. The recorded metrics included MRT-RT and MRT-ACC, while fNIRS was simultaneously used to record activation levels across various brain regions during the completion of the mental rotation task.

2.5 Experimental Instruments and Data Acquisition

fNIRS Data Acquisition: Data were collected using the Shimadzu LIGHTNIRS portable functional near-infrared spectroscopy (fNIRS) system. This system utilizes three wavelengths of near-infrared light (780 nm, 805 nm, and 830 nm) with a sampling rate of 13.33 Hz.

The optode layout consisted of a 2×8 array, comprising 8 emitters and 8 detectors. With an inter-optode distance of 3.0 cm, this configuration established a total of 20 measurement channels. The spatial coordinates of each optode were determined using a FASTRAK 3D digitizer. Subsequently, spatial registration was performed via the NIRS_{SPM} software to map the channel coordinates onto the Montreal Neurological Institute (MNI) standard space. These coordinates were then correlated with the adult Brodmann atlas to define the corresponding brain regions. Based on the core design of the VR "motor-cognitive" dual-task training, this study specifically identified eight Regions of Interest (ROIs) to capture the neural interactions involved in motor execution, sensory integration, and high-level cognitive control, as detailed below.

- Left Frontopolar Area (L-FPA): ch2, ch3, ch6, ch7
- Right Frontopolar Area (R-FPA): ch1, ch2, ch4, ch5
- Left Orbitofrontal Cortex (L-OFC): ch9, ch10
- Right Orbitofrontal Cortex (R-OFC): ch8, ch9
- Left Somatosensory Association Cortex (L-SAC): ch16, ch19, ch20
- Right Somatosensory Association Cortex (R-SAC): ch15, ch18, ch19
- Left Primary Motor Cortex (L-M1): ch12, ch13, ch17
- Right Primary Motor Cortex (R-M1): ch11, ch12, ch14

[Figure 2: see original paper]

Note: The left image shows the prefrontal lobe, and the right image shows the parietal lobe. VR Equipment: An HTC VIVE PRO VR headset system (resolution: 2880 × 1600 pixels; field of view: up to 120°; refresh rate: 90 Hz), equipped with two base stations and two Tracker position sensors.

Heart Rate Monitoring Equipment: A DOMOR sports watch was utilized to monitor real-time heart rate.

2.6 Data Processing and Analysis

fNIRS Data: The preprocessing and analysis of raw data were conducted using the Matlab (R2013b) platform. Initially, raw light intensity data were converted into optical density (OD) data. Subsequently, the relative concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) were calculated using the modified Beer-Lambert law. Preprocessing involved several key steps: (1) Motion artifact correction was implemented using a wavelet transform algorithm (utilizing the 'db4' wavelet base, 5-level decomposition, and an adaptive threshold selection method) [**?**]. (2) Filtering: High-pass filtering was first applied to remove baseline drift, with the cutoff frequency set at 0.01 Hz [**?**]. This was followed by low-pass filtering to suppress high-frequency physiological noise, with a cutoff frequency set at 0.2 Hz. (3) During the concentration conversion process, the processed OD data were transformed into HbO and HbR relative concentration time-series data via the modified Beer-Lambert law.

Spatial registration was completed based on the 10-5 system, and the anatomical brain regions corresponding to each channel were determined through optode localization within the MNI spatial coordinate system. A General Linear Model (GLM) was designed for the preprocessed HbO/HbR concentration data. The design matrix was generated by convolving the task conditions with a standard hemodynamic response function (HRF) including time derivatives. Low-frequency drifts within the model were filtered out using a 0.02 Hz high-pass filter to obtain the β values for each channel under the task conditions. The arithmetic mean of the β values for all channels within each Region of Interest (ROI) was then calculated and used as the activation index for that specific brain region. Finally, SPSS 27.0 was used to perform a two-way repeated measures ANOVA on the channel data before and after the intervention. Behavioral Data: First, normality tests were conducted on the SBSOD scale scores, MRT-ACC, and MRT-RT for the four groups before and after the intervention. The S-W test results showed that $p > 0.05$, indicating a normal distribution. Then, a two-way repeated measures ANOVA (Group × Time) was employed for statistical analysis. In cases involving multiple comparisons, the Benjamini–Hochberg procedure was utilized to control the false discovery rate. After correction, a threshold of $p < 0.05$ was considered to indicate statistical significance [**?**].

Machine Learning Analysis: To quantify the unique effects produced by different interventions at the level of neural patterns, this study employed machine learning methods for auxiliary analysis. The classification model construction process, utilizing the Random Forest algorithm, was executed in a Python 3.9.13 environment. The feature set comprised 16 variables: the pre-intervention baseline activation values for 8 regions of interest (ROIs), and the corresponding change in activation for these ROIs (Δ value = post-intervention - pre-intervention). Three binary classification tasks were designed:

Comparative analyses were conducted between the control group and the VR cognitive group, the control group and the VR exercise group, and the control group and the VR combined exercise-cognitive dual-task group. Leave-one-out cross-validation (LOOCV) was implemented to evaluate model performance, and a grid search method was applied during the hyperparameter optimization process. Multiple evaluation criteria, including accuracy, Area Under the Curve (AUC), precision, recall, and F1 score, were used to measure model performance. Finally, the identification of key neurobiological markers was achieved through feature importance ranking.

3.1.1 SBSOD Scale Scores

A 4 (Group) × 2 (Time) repeated measures ANOVA was conducted on the SBSOD scores. The results (see [Figure 3: see original paper]) revealed a significant main effect of time $[F(1,116) = 268.05, p < 0.001, \eta_p^2 = 0.70]$, a significant main effect of group $[F(3,116) = 90.26, p < 0.001, \eta_p^2 = 0.70]$, and a significant interaction effect between the two $[F(3,116) = 126.08, p < 0.001, \eta_p^2 = 0.77]$.

Simple effects analysis revealed that the main effect of group was not significant at the pre-test $[F(3,116) = 0.61, p = 0.607, \eta_p^2 = 0.02]$. However, at the post-test, the main effect of group was significant $[F(3,116) = 158.52, p < 0.001, \eta_p^2 = 0.80]$. Specifically, scores in the VR motor-cognitive dual-task group were significantly higher than those in the VR motor group ($p < 0.001$), the VR cognitive group ($p < 0.001$), and the control group ($p < 0.001$). The VR motor group scored significantly higher than the control group ($p = 0.002$), and the VR cognitive group also scored significantly higher than the control group ($p < 0.001$); no significant difference was observed between the VR motor and VR cognitive groups. Within the VR motor-cognitive dual-task group, the main effect of time was significant $[F(1,116) = 612.40, p < 0.001, \eta_p^2 = 0.84]$. Similarly, the VR motor group showed a significant main effect of time $[F(1,116) = 19.15, p < 0.001, \eta_p^2 = 0.14]$.

In the VR cognitive group, the main effect of time was also significant $[F(1,116) = 14.70, p < 0.001, \eta_p^2 = 0.11]$. For all three intervention groups, SBSOD scores were significantly higher following the intervention than before. In contrast, the main effect of time for the control group was not significant $[F(1,116) = 0.04, p = 0.832, \eta_p^2 = 0.01]$, indicating no significant difference between pre-test and post-test scores.

[Figure 3: see original paper]

Note: *ns* indicates no significant difference ($p \geq 0.05$), ** $p < 0.01$, *** $p < 0.001$; the same applies hereafter.

3.1.2 Mental Rotation Task Accuracy

The results of the ANOVA for MRT-ACC (see [Figure 4: see original paper]) revealed a significant main effect of time $[F(1,116) = 53.93, p < 0.001, \eta_p^2 =$

0.32], a significant main effect of group [$F(3,116) = 16.75, p < 0.001, \eta_p^2 = 0.30$], and a significant interaction between the two [$F(3,116) = 14.41, p < 0.001, \eta_p^2 = 0.27$]. Simple effects analysis indicated that there was no significant main effect of group at the pre-test [$F(3,116) = 0.51, p = 0.679, \eta_p^2 = 0.01$]. However, at the post-test, the main effect of group was significant [$F(3,116) = 31.10, p < 0.001, \eta_p^2 = 0.45$]. Specifically, the accuracy of the VR motor-cognitive dual-task group was significantly higher than that of the VR motor group ($p < 0.001$), the VR cognitive group ($p < 0.001$), and the control group ($p < 0.001$). The accuracy of the VR motor group was significantly higher than that of the control group ($p = 0.007$). The accuracy of the VR cognitive group was also significantly higher than that of the control group ($p < 0.001$), while no significant difference was found between the VR motor group and the VR cognitive group.

Within the VR motor-cognitive dual-task group, the main effect of time was significant [$F(1,116) = 73.48, p < 0.001, \eta_p^2 = 0.39$]. Significant main effects of time were also observed in the VR motor group [$F(1,116) = 12.66, p = 0.001, \eta_p^2 = 0.10$] and the VR cognitive group [$F(1,116) = 10.55, p = 0.002, \eta_p^2 = 0.08$]. In all three experimental groups, post-intervention accuracy was significantly higher than pre-intervention accuracy. In contrast, the control group did not show a significant main effect of time [$F(1,116) = 0.48, p = 0.492, \eta_p^2 = 0.01$], indicating no significant difference between pre- and post-intervention performance.

[Figure 4: see original paper]

3.1.3 Mental Rotation Task Reaction Time

The results of the ANOVA for MRT-RT (see [Figure 5: see original paper]) revealed a significant main effect of time [$F(1,116) = 57.86, p < 0.001, \eta_p^2 = 0.33$], a significant main effect of group [$F(3,116) = 8.81, p < 0.001, \eta_p^2 = 0.19$], and a significant interaction effect between the two [$F(3,116) = 8.66, p < 0.001, \eta_p^2 = 0.18$].

Simple effects analysis indicated that the main effect of group was not significant at the pre-test [$F(3,116) = 0.45, p = 0.718, \eta_p^2 = 0.01$]. At the post-test, the main effect of group was significant [$F(3,116) = 21.36, p < 0.001, \eta_p^2 = 0.36$]. Specifically, the reaction times of the VR motor-cognitive dual-task group were significantly shorter than those of the VR motor group ($p < 0.001$), the VR cognitive group ($p < 0.001$), and the control group ($p < 0.001$). Reaction times for the VR motor group were significantly shorter than those of the control group ($p = 0.031$), and reaction times for the VR cognitive group were also significantly shorter than those of the control group ($p = 0.032$); however, no significant difference was observed between the VR motor and VR cognitive groups. Within the VR motor-cognitive dual-task group, the main effect of time was significant [$F(1,116) = 60.30, p < 0.001, \eta_p^2 = 0.34$]. Significant main effects of time were also found for the VR motor group [$F(1,116) = 8.36, p = 0.005, \eta_p^2 = 0.07$] and the VR cognitive group [$F(1,116) = 14.65, p < 0.001, \eta_p^2 = 0.11$], with all three groups showing significantly shorter reaction times after the intervention. In contrast, the main effect of time for the control group was not significant [$F(1,116) = 0.53, p = 0.467, \eta_p^2 = 0.01$], indicating no significant difference before and after the intervention period.

[Figure 5: see original paper]

3.2 fNIRS Results

To examine the impact of the intervention on brain activation, a 4 (Group) × 2 (Time) repeated measures ANOVA was conducted on the β values of eight regions of interest (ROIs). Descriptive statistics are presented in , and the activation patterns for brain regions with significant interaction effects are shown in [Figure 6: see original paper].

In the right frontopolar area (R-FPA), the main effect of time was significant [$F(1,116) = 26.22, p < 0.001, \eta_p^2 = 0.18$], while the main effect of group was not significant [$F(3,116) = 1.72, p = 0.168, \eta_p^2 = 0.04$]. However, a significant interaction effect between time and group was observed [$F(3,116) = 3.15, p = 0.028, \eta_p^2 = 0.08$]. Simple effect analysis revealed that there was no significant main effect of group at the pre-test [$F(3,116) = 0.15, p = 0.929, \eta_p^2 = 0.04$]. At the post-test, the main effect of group was significant [$F(3,116) = 5.12, p = 0.002, \eta_p^2 = 0.12$]. Specifically, activation in the VR motor-cognitive dual-task group, the VR motor group, and the VR cognitive group was significantly lower than that of the control group ($p < 0.001, p = 0.011, p = 0.012$, respectively), while no significant differences were found between the three intervention groups. For the VR motor-cognitive dual-task group, the main effect of time was significant [$F(1,116) = 14.24, p < 0.001, \eta_p^2 = 0.11$]. Similarly, the VR motor group showed a significant main effect of time [$F(1,116) = 9.20, p = 0.003, \eta_p^2 = 0.07$]. The VR cognitive group also exhibited a significant main effect of time [$F(1,116) = 12.23, p = 0.001, \eta_p^2 = 0.10$]. In all three intervention groups, brain activation after the intervention was significantly lower than before the intervention. In contrast, the control group did not show a significant main effect of time [$F(1,116) = 0.01, p = 0.950, \eta_p^2 = 0.01$], indicating no significant difference between pre- and post-test measurements.

In the left frontopolar area (L-FPA), the main effect of time was significant [$F(1,116) = 39.85, p < 0.001, \eta_p^2 = 0.26$], the main effect of group was significant [$F(3,116) = 4.16, p = 0.008, \eta_p^2 = 0.10$], and the interaction effect between the two was also significant [$F(3,116) = 5.22, p = 0.002, \eta_p^2 = 0.12$]. Simple effect analysis indicated that the main effect of group was not significant at the pre-test [$F(3,116) = 0.20, p = 0.894, \eta_p^2 = 0.01$]. At the post-test, the main effect of group was significant [$F(3,116) = 8.12, p < 0.001, \eta_p^2 = 0.17$]. Activation in the VR motor-cognitive dual-task group was significantly lower than in the VR motor group ($p = 0.008$), the VR cognitive group ($p = 0.007$), and the control group ($p < 0.001$). No significant differences were observed between the VR motor group, the VR cognitive group, and the control group

($p \geq 0.05$). Regarding the main effect of time, significant results were found for the VR motor-cognitive dual-task group [$F(1, 116) = 40.27, p < 0.001, \eta_p^2 = 0.26$], the VR motor group [$F(1, 116) = 9.23, p = 0.003, \eta_p^2 = 0.07$], and the VR cognitive group [$F(1, 116) = 5.01, p = 0.027, \eta_p^2 = 0.04$]. In these three groups, brain activation was significantly lower post-intervention compared to pre-intervention. The control group showed no significant main effect of time [$F(1, 116) = 1.00, p = 0.318, \eta_p^2 = 0.01$], with no significant changes observed between the two time points.

In the right primary motor cortex (R-M1), the main effect of time was significant [$F(1, 116) = 15.79, p < 0.001, \eta_p^2 = 0.12$], the main effect of group was significant [$F(3, 116) = 4.30, p = 0.006, \eta_p^2 = 0.10$], and their interaction was significant [$F(3, 116) = 6.61, p < 0.001, \eta_p^2 = 0.15$]. Simple effect analysis showed that the main effect of group was not significant at the pre-test [$F(3, 116) = 0.26, p = 0.854, \eta_p^2 = 0.01$]. At the post-test, the main effect of group was significant [$F(3, 116) = 10.10, p < 0.001, \eta_p^2 = 0.21$]. The VR motor-cognitive dual-task group showed significantly lower activation than the VR motor group ($p < 0.001$), the VR cognitive group ($p < 0.001$), and the control group ($p < 0.001$). There were no significant differences between the VR cognitive group, the VR motor group, and the control group ($p \geq 0.05$). For the VR motor-cognitive dual-task group, the main effect of time was significant [$F(1, 116) = 33.22, p < 0.001, \eta_p^2 = 0.22$], with brain activation significantly lower after the intervention ($p < 0.001$). However, the main effect of time was not significant for the VR motor group [$F(1, 116) = 0.29, p = 0.591, \eta_p^2 = 0.02$], the VR cognitive group [$F(1, 116) = 2.06, p = 0.154, \eta_p^2 = 0.02$], or the control group [$F(1, 116) = 0.05, p = 0.833, \eta_p^2 = 0.01$]. No significant differences between pre- and post-intervention were found in these three groups. Furthermore, the main effects of time and group, as well as their interaction, were not significant for the left primary motor cortex (L-M1), right orbitofrontal cortex (R-OFC), left orbitofrontal cortex (L-OFC), right somatosensory association cortex (R-SAC), and left somatosensory association cortex (L-SAC).

[Figure 6: see original paper]

3.3 Machine Learning Analysis of Neural Pattern Differences

A random forest model was employed to distinguish between the intervention group and the control group, utilizing a 16-dimensional neural feature set. This feature set was constructed based on the baseline activation levels of eight Regions of Interest (ROIs) and their corresponding changes (Δ values) following the intervention. The performance metrics for the three classification tasks are presented in , while the rankings of key feature importance are illustrated in [Figure 7: see original paper] through [Figure 10: see original paper].

[Figure 7: see original paper] [Figure 8: see original paper] [Figure 9: see original paper] [Figure 10: see original paper]

Control Group vs. VR Cognitive Group: The model achieved a classification accuracy of 82% with an AUC value of 0.83, indicating that the model can effectively distinguish between the two groups. The most discriminative neural features were the changes in activation levels within the left frontopolar area (Delta_L-FPA) and the right frontopolar area (Delta_R-FPA).

Control Group vs. VR Exercise Group: The model' s classification accuracy was 65% with an AUC of 0.66. This relatively lower performance suggests that the neural patterns induced by pure exercise intervention have limited distinctiveness compared to the control group. The most significant features remained Delta_L-FPA and Pre_R-FPA.

Control Group vs. VR Exercise-Cognitive Dual-Task Group: The model achieved a classification accuracy of 80% and an AUC of 0.79, demonstrating robust discriminative capability. The most critical feature shifted to the change in activation within the right primary motor cortex (Delta_R-M1), followed by the left frontopolar area (Delta_L-FPA). This pattern of feature importance differs starkly from the single-task groups, suggesting that dual-task training shapes a unique neural activity pattern that integrates both motor and cognitive components.

4 Discussion

This study systematically explores the facilitative effects of VR motor-cognitive dual-task training on the spatial visualization abilities of individuals with low spatial ability, as well as the underlying neuroplasticity mechanisms, by integrating behavioral measurements, fNIRS functional brain imaging, and machine learning methods. Behavioral results indicated that after 8 weeks of training, all intervention groups showed significant improvements in spatial visualization ability. Notably, the improvement in the VR motor-cognitive dual-task group was significantly greater than that of the two single-task groups, both of which outperformed the no-intervention control group. This finding strongly supports the primary hypothesis of this study: a dual-task synchronous training model that integrates physical movement with cognitive processing possesses unique advantages in enhancing spatial ability.

The advantages observed at the behavioral level can be attributed to the high degree of alignment between the training model and embodied cognition theory. The self-developed VR training system used in this study serves as an ideal vehicle for realizing embodied cognition; it not only simulates visuospatial environments but also supports real-time navigation, manipulation, and feedback through physical movements, thereby establishing a tight coupling loop between perception and action. By synchronizing virtual displacement driven by stationary running with spatial navigation tasks in real-time, the VR motor-cognitive dual-task intervention enables cognitive processing—such as map recognition and route planning—to be completed during physical exercise. This achieves a deep coupling of physical action and cognitive operation [?]. Such "motor-cognitive" interactive synchronous training continuously strengthens the understanding of spatial relationships and the ability to mentally manipulate 3D objects. Specifically, during the target search phase, practitioners must determine the map orientation of the target point and rotate the map perspective in their minds based on their physical orientation. During the cognitive map construction phase, changes in direction while moving cause the positions of landmarks within the mental map to rotate along with the perspective [?]. In the scene representation phase, participants must correspond real-world landmarks with map symbols and adjust their spatial representations based on their current location and orientation [?, ?]. The brain executes efficient integration and real-time updating of multimodal sensory information, including visual, proprioceptive, and vestibular cues. This "cognition-in-action" phenomenon significantly enhances the flexibility of spatial working memory and its mental representations. In contrast, the VR motor group, which only performed running along a fixed route, lacked sufficient high-level cognitive engagement. The VR cognitive group, which performed navigation via a controller, lacked critical bodily movement feedback. The optimization of the overall "body-cognition" system efficiency likely stems from the behavioral gain effects of dual-task training, echoing the core tenets of embodied cognition theory [?].

At the neural level, the brain activation patterns revealed by fNIRS provide empirical evidence for the unique benefits of different training modes. The most significant and specific neuroplasticity changes were induced by the VR motor-cognitive dual-task training, where activation levels in the R-FPA, L-FPA, and R-M1 decreased significantly post-intervention. The decrease in activation levels in the L-FPA and R-M1 was notably larger compared to the VR motor and VR cognitive groups. Decoding results from the machine learning model showed that the neural activity patterns of the control group and the VR motor-cognitive dual-task group were highly distinguishable, with the change in activity in the R-M1 and L-FPA identified as the most discriminative classification features. Although the VR motor and VR cognitive groups also showed significantly reduced activation in the R-FPA and L-FPA after intervention, the magnitude of change was relatively small, and the key classification features identified by the machine learning model remained concentrated in FPA activity changes. These results validate the neural efficiency hypothesis proposed by [?], suggesting that highly trained individuals can complete cognitive tasks of the same difficulty with lower consumption of cognitive resources. The broader reduction in brain activation and superior neural pattern discriminability observed in the VR motor-cognitive dual-task group indicate that this training mode significantly enhances neural efficiency. The underlying mechanism may lie in the synchronous cognitive demands unique to this training—such as real-time route planning, map recognition, and spatial working memory updating—which place higher information-processing demands on the brain [?]. These continuous and complex cognitive challenges promote the functional optimization and reorganization of relevant neural circuits, achieving a more economical and efficient neural resource recruitment pattern [?]. This finding is highly consistent with research on orienteering athletes [?], suggesting that long-term motor-cognitive integrated practice can shape more efficient patterns of neural resource utilization.

From the functional perspective of specific brain regions, the prefrontal cortex, particularly the frontopolar area (FPA), plays a vital role in high-level cognitive activities, including decision-making, problem-solving, and attentional control [?, ?]. The FPA, a key subregion of the prefrontal cortex, is primarily responsible for information integration, logical reasoning, and error monitoring; it is also significantly associated with the maintenance and updating of working memory [?]. When performing mental rotation tasks, the FPA is crucial for integrating information across multiple brain regions and implementing cognitive control, which in turn facilitates the formation of coherent cognitive representations of the spatial environment [?]. Simultaneously, the R-M1 is responsible for integrating visuospatial information with bodily proprioceptive signals, playing a central role in constructing 3D spatial representations. This integration function is directly linked to the neural basis of mental rotation tasks, which rely on sensorimotor simulation mechanisms that integrate visuospatial processing and motor representation at the neural level [?]. Thus, it can be inferred that the multimodal information integration performed by the R-M1 provides the necessary neural foundation for spatial representation construction during mental rotation. Furthermore, brain function exhibits hemispheric lateralization: the left hemisphere dominates linear thinking, language processing, and logical reasoning, while the right hemisphere excels at spatial perception tasks and image processing. The differences in bilateral activation observed during mental rotation tasks may be related to this lateralization [?]. In summary, the reason the VR motor-cognitive dual-task group induced highly specific and easily identifiable neural activity patterns is that this training mode achieves synchronized and deep activation optimization of both the "cognitive regulation" and "spatial integration" systems. Consequently, the FPA and R-M1 functional systems form an efficient and collaborative working network architecture. In contrast, single-mode training relies primarily on the operation of only one of these systems, resulting in neural patterns with relatively limited uniqueness.

This study reveals the effective pathway through which VR motor-cognitive dual-task training enhances spatial visualization ability from a mechanistic perspective, providing multimodal evidence for the theory of "body-cognition integration" and establishing a methodological foundation for developing precision cognitive training paradigms based on objective neural markers. However, as a technology-assisted method, VR training still has inherent limitations. Some subjects may experience mild motion sickness or visual fatigue during long-term training, affecting the experience. Additionally, differences exist between virtual and real environments at the perception-action level; whether the skills acquired through training can transfer to daily life remains to be verified. Furthermore, high hardware costs restrict the widespread promotion of this intervention in clinical or community settings. It should also be noted that this study only verified the short-term effects of a specific dual-task paradigm; its long-term sustainability and transfer effects to real-world scenarios require further longitudinal investigation. Moreover, fNIRS technology has inherent limitations in spatial resolution, as its signals primarily reflect cortical activity, making it difficult to precisely locate and analyze functional changes in deep brain regions. Future research could be expanded in the following areas: first, focus on enhancing ecological validity and testing transfer effects to systematically explore the boundary conditions of "motor-cognitive" interactions in different environmental contexts, thereby comprehensively evaluating the practical applicability and promotional value of this training model. Second, regarding technical methods, researchers could attempt to integrate multimodal technologies such as fMRI, eye-tracking, and EEG to complement fNIRS, providing more comprehensive coverage of the brain' s spatial cognitive network and strengthening the in-depth investigation of whole-brain functional connectivity and dynamic processing.

5 Conclusion

VR motor-cognitive dual-task training effectively enhances the spatial visualization abilities of individuals with low spatial capacity, yielding behavioral benefits significantly superior to those of single VR motor training or VR cognitive training. These behavioral gains emerge alongside an optimization of neural efficiency, specifically characterized by a marked decrease in activation levels within the R-M1 and L-FPA. This suggests an increased level of automation within the sensory-motor integration system and cognitive control processes. Furthermore, machine learning models successfully decoded the unique neural activity patterns induced by dual-task training.

The L-FPA was identified as a key feature across all three experimental groups, reflecting a universal neural change resulting from intervention training. In contrast, the R-M1 was stably identified with the highest weight only in the VR motor-cognitive dual-task group, serving as a unique and critical biomarker for that specific condition. This indicates that dual-task training shapes a highly specific and quantifiable "motor-cognitive" synergistic neural pattern, confirming the deep integration of body and cognition within neural representations at a computational level. By examining behavioral outcomes, brain mechanisms, and computational features, this study systematically reveals the positive effects and neural foundations of VR motor-cognitive dual-task training in enhancing spatial ability. These findings provide solid empirical evidence and methodological support for the development of precision cognitive intervention programs based on the theory of "embodied-cognitive" integration.

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