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# Ergonomic Evaluation of Manned Submersibles Based on Simulation Operations

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**Abstract.** As the central component of the human-machine interface within manned submersible, oceanauts are entrusted with vital responsibilities such as deep-sea navigation and the operation of manipulators. To bolster the selection process of pilots and their routine training, the "Deep-Sea Manned Submersible Simulation Operation System V1.0" has been meticulously developed. This sophisticated system, modeled after the "Jiaolong" submersible, leverages the cutting-edge capabilities of 3dsMax and Unity3D platforms, seamlessly integrating six core modules: human-computer interaction, motion dynamics, collision detection, visual simulation, special effects, and audio components.Within the scope of this study, the Vienna Test System (VTS) was employed to deliver a comprehensive cognitive training regimen, aimed at enhancing bimanual coordination, selective attention, and spatial memory skills. Participants underwent simulated driving and manipulator tasks both prior to the commencement of training and at the 5-day and 10-day marks post-training. The driving tasks simulated the challenges of navigating through intricate environments such as abyssal plains, seamounts, and hydrothermal vent regions, while manipulator tasks demanded precise spatial orientation, skillful grasping, and the execution of intricate operations.To evaluate ergonomic performance and task efficiency, a suite of physiological indicators was monitored, including prefrontal oxygenated hemoglobin (HbO) concentration, mean arterial pressure (MAP), inter-beat interval (IBI), left ventricular ejection time (LVET), stroke volume (SV), and total peripheral resistance (TPR). The findings of the study suggest that engagement in simulation operations significantly impacts ergonomic indicators, and that cognitive training plays a pivotal role in bolstering physiological responses and improving task performance within operational scenarios.

**Keywords:** Manned submersible; Human-computer interaction; Cognitive training; Ergonomic; Simulation operations.

## 1. Introduction

With the rapid development of China's deep-sea resource exploration and exploitation, the operational frequency and dive depth of the "Jiaolong," "Shenhai Yongshi," and "Fendouzhe" series of manned submersibles are continuously increasing. As a core element of the human-machine-environment system in manned submersibles, pilots undertake dual responsibilities in submersible navigation and operational tasks. Their working environment is characterized by several notable features: firstly, significant environmental influences. Pilots must maintain irregular seated positions in confined cabins for extended periods, enduring extreme temperatures, noise, vibration, and acceleration. Additionally, during submersible deployment and retrieval, they undergo transitions between surface and deep-sea environments, facing unpredictable factors such as sea winds and waves and changes in light, water temperature, terrain, and pressure. Secondly, the high complexity of the human-machine system. Pilots must simultaneously manage navigation operations and scientific tasks, monitor internal and external parameters in real time, process large volumes of information, operate complex instruments for navigation, and perform underwater manipulator operations. Lastly, high operational intensity. During predetermined operational periods, pilots conduct daily dives, with single dive durations exceeding 10 hours. These factors can result in physiological changes, affecting their health, work efficiency, and the reliability and safety of deep-sea operations. Thus, exploring changes in physiological function and performance under different operational tasks is essential for reducing fatigue, minimizing errors, enhancing safety,

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preventing occupational diseases, safeguarding health, and improving training systems.Due to the confined space within manned submersibles, conducting ergonomic research in real environments is challenging, with difficulties in controlling experimental conditions, high costs, and limited data collection. Hence, simulation systems are widely used for related studies globally. Zhang Xiaoxi et al. addressed the high training costs and risks associated with the "Jiaolong" submersible’s manipulator operations by establishing a three-dimensional physical model using the D-H method for kinematic modeling and solutions. They developed a validation platform using VC++ and OpenGL, integrating virtual reality technology for interactive simulation of underwater manipulator operations, significantly enhancing training efficiency and reducing costs[1-2]. Li Dejun et al. conducted kinematic and dynamic modeling of the "Jiaolong" submersible’s HOV manipulator, analyzing forward and inverse kinematics, and using MATLAB for simulation validation, employing the Lagrangian method for dynamic modeling. They considered the impact of submersible motion on the manipulator, validating kinematic and dynamic models through simulation[3]. Deng C et al. developed kinematic and dynamic models for the "Fendouzhe" submersible, employing LSTM neural networks to estimate system disturbances, enhancing simulation accuracy and validity when compared with experimental data[4]. Liu K et al. developed a semi-physical virtual reality system for manned submersible control research, featuring control nodes, virtual sensor nodes, and visualization nodes. This system allows MSV software testing in laboratory environments, reducing experimental risks, effectively verifying new underwater vehicle systems' performance, and enabling efficient, cost-effective intensive testing[5]. Zhang Yichi et al. proposed optimization suggestions for manned submersibles based on digital ergonomic simulation evaluations, improving human-machine ergonomics at control consoles. They analyzed human-machine interaction needs, proposed system design methods, and established human factors evaluation metrics to enhance pilot control efficiency, safety, and comfort[6-7]. Fu Binguo et al. introduced a virtual reality-based manipulation simulation system for manned submersibles, simulating underwater motion and addressing critical issues in visualization modeling and real-time display, enhancing training effects[8-9].

In simulation studies of driver ergonomics, physiological measurement, subjective measurement, and performance measurement are key evaluation methods. Physiological measurement objectively assesses drivers' physiological state and fatigue levels through real-time monitoring of heart rate and blood pressure, though it can be complex and invasive. Subjective measurement evaluates comfort and satisfaction through questionnaires and self-reports, being simple and cost-effective but subject to personal differences and difficult to quantify. Performance measurement directly assesses driving safety through performance metrics like reaction time and error rate, though it may overlook physiological and psychological states and be influenced by test environments. Shi Lu et al. recorded and analyzed various physiological and psychological indicators in simulated and actual diving scenarios. Results indicate significant increases in heart rate, changes in sympathetic-vagal balance, increased theta wave relative power, and decreased alpha wave relative power during actual deep-sea dives, with reduced brain arousal levels in later stages[10-13]. Evaluations of manned submersible cabin environments and human-machine interfaces by Shi Lu et al. also identified lower limb blood flow and SEMG as valuable indicators for assessing fatigue in irregular sitting postures. Behavioral metrics such as visual task accuracy and reaction time, along with eye movement data like visual fixation duration and pupil diameter, are crucial considerations for human-machine interface design and optimization[14-15].Manned aerospace and deep-sea exploration are key focus areas in China’s frontier technological development. In September 2014, the globally recognized journal "Science" introduced a special English edition titled "Human Performance in Space: Advancing Astronautics Research in China," showcasing innovative academic research in human factors engineering in China’s manned spaceflight program. In terms of hardware, China has completed the strategic layout of the 4,500-meter "Shenhai Yongshi," 7,000-meter "Jiaolong," and 11,000-meter full-ocean-depth "Fendouzhe" manned submersibles. This project aims to utilize a self-developed deep-sea manned submersible simulation operation

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visualization human-machine interaction platform system to conduct ergonomic evaluations of physiological and task performance indicators under various operational tasks and difficulty levels, providing references for optimizing manned submersible human-machine systems and pilot selection and training.

## 2. Deep-Sea Manned Submersible Simulation Operation System

### 2.1 Overall Design

To enhance pilot training efficiency and improve their physiological and psychological endurance in complex deep-sea environments, as well as systematically evaluate their judgment and decision-making abilities under various deep-sea operational conditions, the research team developed the "Deep-Sea Manned Submersible Simulation Operation System V1.0" based on 3dsMax and Unity3D software platforms. This system was awarded a computer software copyright registration certificate by the National Copyright Administration of the People's Republic of China (Registration No.: 2019SR1160310). Modeled on the "Jiaolong" manned submersible, the system simulates the operation process of deep-sea manned submersibles by constructing a cockpit display and control interface and a human-machine system. The system employs a modular design, consisting of six main modules: human-computer interaction, motion, collision detection, visual simulation, special effects, and sound modules. System testing and user feedback indicate high simulation accuracy and user experience, effectively supporting pilot training and mission planning[16-17].

### 2.2 Human-Computer Interaction Module

The submersible's control utilizes a dual-joystick input mechanism. One three-axis joystick is used to control the horizontal movement of the submersible, including forward/backward, left/right shift, and left/right rotation. The other two-axis joystick controls the vertical movement, including ascent/descent and pitch forward/backward. The joysticks connect to the computer via USB, and the system uses Unity3D engine's Input function to acquire real-time input values for each degree of freedom, mapping them to the submersible's motion parameters to ensure precision and real-time operation. The manipulator is controlled using gamepad button inputs, simulating multi-degree-of-freedom motion. The manipulator structure comprises three links and a mechanical claw, with a total of seven degrees of freedom ($\theta1 \sim \theta7$), geometrically modeled using 3dsMax based on actual dimensions. To simulate the multi-degree-of-freedom motion of the manipulator, the system employs Configurable Joints for connections, specifically between Link 1 and the hull, between the links, and between Link 3 and the mechanical claw.

## 3. Ergonomic Evaluation Experiment Design

### 3.1 Subjects and Methods

Eight male volunteers participated, with an age of (24.8±1.8) years, height of (171.8±6.7) cm, weight of (65.0±10.4) kg, right-handed, and with normal or corrected vision. All participants underwent training on the submersible simulation system before the experiment, mastering all operational tasks, and achieving the required standards in simulated driving performance. Informed consent was obtained from all participants regarding the experimental content. The experiment used a within-subject design over 13 days. Simulated driving tasks were conducted on days 1, 7, and 13. Cognitive training, lasting 1 hour each day, was conducted from days 2 to 6 and 8 to 12. Before the experiment (day 0), baseline ergonomic physiological indicators were collected at rest. Ergonomic physiological data during simulated driving tasks were collected before cognitive training (day 1), after 5 days of cognitive training (day 7), and after 10 days of cognitive training (day 13). VTS was used for cognitive training focusing on bimanual coordination, selective attention, and spatial

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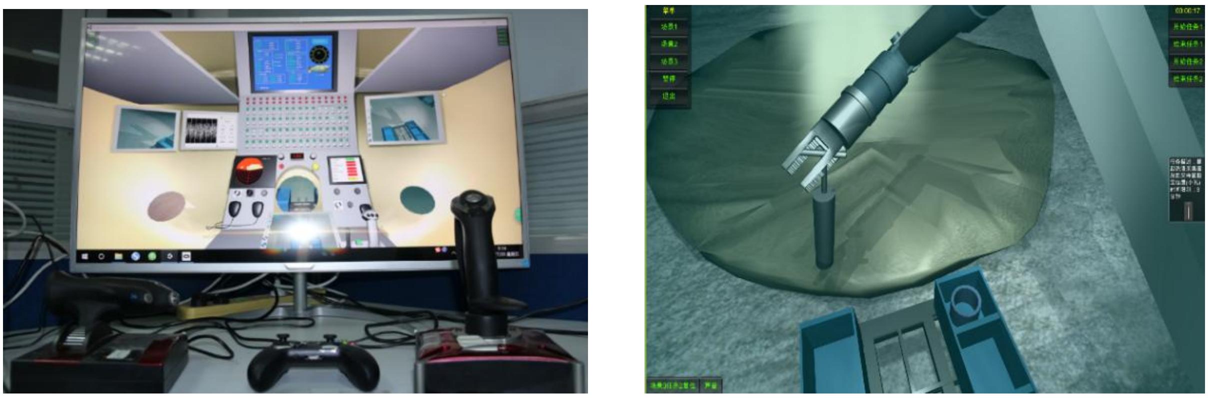
memory, as shown in Table 1. The manned submersible simulation tasks were divided into driving and manipulator types, each with three subtasks lasting 3 minutes, with a counterbalanced order among participants, as shown in Table 2. Examples of simulated driving tasks can be seen in Figure 1(a), and manipulator tasks in Figure 1(b).

Table 1. Cognitive training programs and content

| Training Program | Duration | Content |
|---|---|---|
| Bimanual Coordination Training | 20 min | Participants are required to move a sector to an inverted T position in a three-dimensional space using dual joysticks, aligning the apex of the sector with the dot on the inverted T, and ensuring the vertical line of the T bisects the area of the sector. |
| Selective Attention Training | 20 min | Before the training begins, participants memorize the image of a target animal and imagine driving a small train through a tunnel where various animals appear. Participants must quickly press a button when the target animal appears, ignoring other irrelevant stimuli. |
| Visual-Spatial Memory Training | 20 min | There are many ships on the sea surface, and the system provides specific cues. Participants need to remember the changes in the ships and reproduce them in sequence. |

Table 2. Simulation operation content of manned submersible

| Task Type | No. | Subtask Name | Task Content |
|---|---|---|---|
| Driving | Subtask 1 | Abyssal Zone | Participants must navigate the submersible to avoid obstacles and reach a designated location within the specified time, maintaining an altitude of 2 to 6 meters above the seabed. The target location is dynamically displayed on the imaging sonar. The task ends upon reaching the location or after the 3-minute time limit. |
| | Subtask 2 | Seamount Zone | |
| | Subtask 3 | Hydrothermal Zone | |
| Manipulator | Subtask 1 | Spatial Positioning | Participants operate the manipulator to touch target objects. They must touch as many targets as possible within 3 minutes. |
| | Subtask 2 | Grasping | Participants operate the manipulator to grasp target objects. Each successful grasp is followed by a reset, and the time is recorded until the 3-minute duration ends. |
| | Subtask 3 | Integrated Operation | The participant needs to grasp target objects and accurately place them into designated positions in the sample basket. Each successful operation is followed by a reset, and the time is recorded until the 3-minute duration ends. |



(a) (b)

Fig. 1 Schematic diagram of simulation operations

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### 3.2 Ergonomics Evaluation Metrics

3.2.1 Physiological indicators

A NIRSport portable near-infrared brain imaging system was used to record real-time changes in HbO levels in the prefrontal cortex under different experimental conditions. The sampling frequency was 7.81 Hz, with 8 light sources and 7 detectors forming 20 channels. The arrangement of light sources and detectors is shown in Figure 5(a), and the corresponding prefrontal cortex regions are shown in Figure 5(b).

A non-invasive hemodynamic monitoring device (FMS PortaPres Model-2) was used to monitor parameters such as MAP, IBI, LVET, SV, and TPR in real-time within 3 minutes after participants completed different simulated tasks.

3.2.2 Performance indicators

Driving Task Performance Indicators:Completion time to reach the destination (s).Deviation distance from the destination at the end of the task (m).Accuracy of maintaining an altitude between 2 m and 6 m throughout the task (%).

Manipulator Task Performance Indicators:Average time to complete each action (s).In Subtask 1, an action refers to successfully touching a target.In Subtask 2, an action refers to successfully grasping a target.In Subtask 3, an action refers to successfully grasping and placing a target object.If the number of successful actions is zero, the time is assigned a value of 180 seconds.

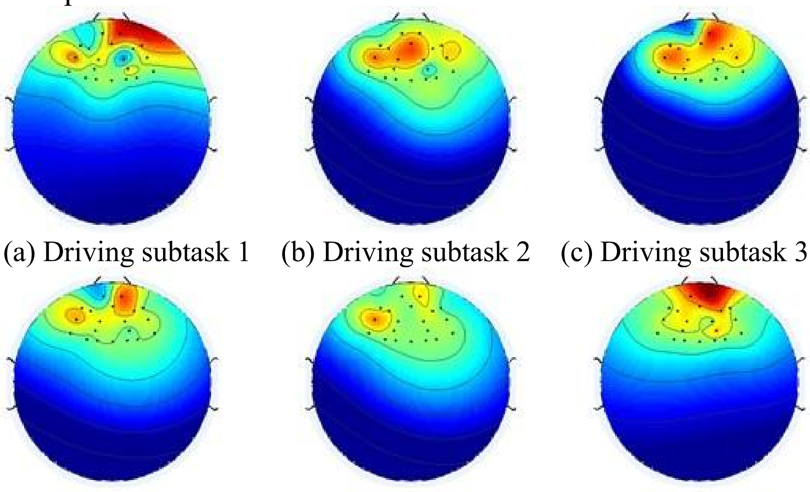
### 3.3 Data Analysis

Repeated measures ANOVA was used to analyze ergonomic physiological data across different groups. If significant differences were observed ($P < 0.05$), post hoc multiple comparisons were conducted using the Bonferroni method.

## 4. Ergonomics Evaluation Results

### 4.1 HbO Concentration

During the data processing phase, manual artifact removal was first performed on the collected signals. Subsequently, a band-pass filter (0.02–0.06 Hz) was applied to extract information within the effective frequency range. For HbO concentration data under different subtasks, the time-averaged values were calculated and averaged across the 8 participants to generate group-level brain topography maps. The average brain topography maps of HbO concentration changes across the 8 participants under different subtasks are shown in Figure 2. By comparing brain activation before and after the tasks, it was observed that the simulated tasks induced significant activation in the prefrontal regions Fp2 and AF3.



(a) Driving subtask 1 (b) Driving subtask 2 (c) Driving subtask 3

(d) Manipulator subtask 1 (e) Manipulator subtask 2 (f) Manipulator subtask 3

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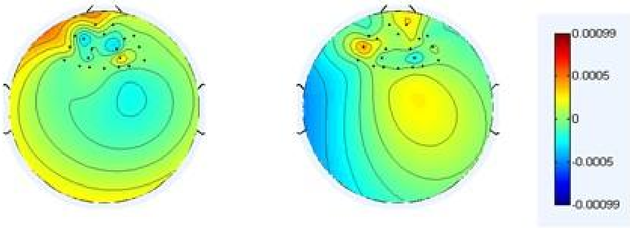


(g) Before Simulated Task (h) After Simulated Task

Fig. 2 Topographic map of cerebral blood flow HbO concentration during simulation operations

### 4.2 Hemodynamic

The hemodynamic parameter changes within 3 minutes after simulated tasks are shown in Table 3. Compared with the control group, both driving and manipulator tasks showed an increasing trend in MAP (mean arterial pressure) and SV (stroke volume) before training, after 5 days, and after 10 days of training. In contrast, IBI (inter-beat interval), LVET (left ventricular ejection time), and TPR (total peripheral resistance) demonstrated a shortening or decreasing trend, with IBI exhibiting significant differences ($P < 0.05$ and $P < 0.01$).Compared with pre-training values for the same subtasks:For driving subtasks, LVET significantly increased in Subtasks 1 and 2 after 10 days of training ($P < 0.05$) and significantly increased in Subtask 3 after both 5 and 10 days of training ($P < 0.05$).For manipulator Subtask 2, MAP significantly decreased ($P < 0.05$), and LVET significantly increased ($P < 0.05$) after 10 days of training.For manipulator Subtask 3, LVET significantly increased after 10 days of training ($P < 0.05$).Compared with the 5-day training results, no significant differences were observed in MAP, SV, IBI, LVET, or TPR after 10 days of training for either task. The observed MAP increase is primarily associated with sympathetic nervous system activation and elevated catecholamine secretion during simulated driving tasks. The increase in SV is attributed to enhanced myocardial contractility induced by sympathetic excitation. The shortened IBI reflects an accelerated heart rate, related to increased sympathetic activity and reduced vagal tone. LVET shortening correlates with faster heart rates and enhanced myocardial contractility. TPR reduction is linked to skeletal muscle vasodilation in response to metabolic demands.

Table 3. Simulation operation content of manned submersible

| Task Type | Group | MAP (mmHg) | IBI（s） | LVET（ms） | SV（mL） | TPR（MU） |
|---|---|---|---|---|---|---|
| Rest | Control | 81.30±10.91 | 0.90±0.21 | 283.14±23.17 | 97.30±16.64 | 0.88±0.33 |
| Driving subtask 1 | Pre-training | 90.24±12.10 | 0.58±0.08 [b] | 255.25±14.22 [a] | 103.22±16.58 | 0.79±0.24 |
| | After 5 days training | 85.21±8.62 | 0.63±0.09 [b] | 267.26±10.23 | 101.22±10.28 | 0.82±0.21 |
| | After 10 days training | 83.55±9.52 | 0.65±0.08 [b] | 270.33±8.98 [c] | 99.84±9.80 | 0.82±0.19 |
| Driving subtask 2 | Pre-training | 88.65±9.52 | 0.59±0.10 [b] | 260.14±10.32 [a] | 105.65±5.98 | 0.78±0.25 |
| | After 5 days training | 86.10±5.84 | 0.64±0.11 [b] | 271.35±12.01 | 102.09±6.41 | 0.83±0.24 |
| | After 10 days training | 84.52±9.18 | 0.67±0.12 [a] | 271.99±9.80 [c] | 103.19±5.88 | 0.81±0.27 |
| Driving subtask 3 | Pre-training | 89.58±5.84 | 0.61±0.08 [b] | 262.54±8.99 [a] | 107.94±7.81 | 0.80±0.31 |
| | After 5 days training | 85.55±10.02 | 0.64±0.10 [b] | 272.84±9.11 [c] | 101.53±9.41 | 0.83±0.14 |
| | After 10 days training | 84.05±8.16 | 0.64±0.07 [b] | 275.83±9.17 [c] | 104.87±8.64 | 0.84±0.19 |
| Manipulator subtask 1 | Pre-training | 91.32±5.21 [a] | 0.59±0.12 [b] | 259.66±8.84 [a] | 106.65±8.43 | 0.76±0.22 |
| | After 5 days training | 87.65±8.81 | 0.63±0.11 [b] | 268.41±10.38 | 99.84±7.91 | 0.79±0.10 |
| | After 10 days training | 85.19±8.17 | 0.66±0.09 [a] | 269.49±11.03 | 102.42±8.88 | 0.81±0.11 |
| Manipulator subtask 2 | Pre-training | 90.55±2.19 [a] | 0.60±0.09 [b] | 261.58±9.44 [a] | 104.99±7.53 | 0.75±0.19 |
| | After 5 days training | 86.42±8.11 | 0.65±0.13 [a] | 271.65±9.84 | 100.05±7.64 | 0.81±0.15 |
| | After 10 days training | 84.14±7.99 [c] | 0.67±0.10 [a] | 272.81±8.17 [c] | 101.76±8.61 | 0.81±0.14 |
| Manipulator subtask 3 | Pre-training | 92.50±6.48 [a] | 0.58±0.11 [b] | 254.96±10.33 [b] | 105.62±7.54 | 0.77±0.15 |
| | After 5 days training | 86.61±8.72 | 0.65±0.08 [b] | 264.64±12.50 | 102.49±6.04 | 0.83±0.11 |
| | After 10 days training | 85.19±8.67 | 0.65±0.09 [b] | 267.11±10.28 [c] | 100.22±7.89 | 0.84±0.20 |

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Note: Compared with control group: aP < 0.05, bP < 0.01; Compared with pre-training values of the same subtask: cP < 0.05.

### 4.3 Task Performance

The task performance changes during simulated tasks are shown in Table 4. The effects of training on task performance during simulated tasks were primarily reflected in completion time and deviation distance:For the driving subtasks, completion time decreased with extended training. After 10 days of training, the completion time for Subtask 2 was significantly shorter compared to pre-training (P < 0.05).Deviation distance decreased for Subtasks 1 and 2 with training progression. For Subtask 2, deviation distance was significantly reduced after both 5 and 10 days of training compared with pre-training (P < 0.001).For manipulator tasks, the average completion time of Subtasks 1 and 2 was significantly reduced after 10 days of training compared with pre-training (P < 0.05 and P < 0.01), while no significant difference was found for Subtask 3.

Table 4. Simulation operation content of manned submersible

| Task Type | Performance Indicators | Pre-training | After 5 days training | After 10 days training |
|---|---|---|---|---|
| Driving subtask 1 | Completion time (s) | 165.8±15.5 | 163.9±14..3 | 154.9±11.6 |
| | Deviation distance (m) | 24.0±41.8 | 13.3±16.5 | 4.1±3.1 |
| | Accuracy (%) | 58.1±14.2 | 59.5±19.3 | 40.7±18.2 |
| Driving subtask 2 | Completion time (s) | 173.8±17.7 | 153.9±23.8 | 146.8±16.2 a |
| | Deviation distance (m) | 96.9±44.3 | 18.8±23.9 c | 11.8±24.1 c |
| | Accuracy (%) | 35.8±8.9 | 41.2±11.1 | 35.7±9.6 |
| Driving subtask 3 | Completion time (s) | 170.4±18.0 | 156.9±19.8 | 150.3±24.3 |
| | Deviation distance (m) | 22.8±21.8 | 8.3±13.5 | 17.8±33.1 |
| | Accuracy (%) | 37.6±7.8 | 33.4±9.3 | 32.0±3.8 |
| Manipulator subtask 1 | Average time (s) | 26.6±9.8 | 19.0±5.0 | 12.9±2.8 b |
| Manipulator subtask2 | Average time (s) | 170.0±18.5 | 124.6±50.5 | 105.4±43.8 a |
| Manipulator subtask 3 | Average time (s) | 180.0±0.0 | 177.4±7.4 | 180.0±0.0 |

Note: Compared with pre-training values: aP < 0.05, bP < 0.01, cP < 0.001.

## 5. Summary

This study systematically investigates human factors and ergonomics issues during simulated operations of deep-sea manned submersibles by developing the "Deep-Sea Manned Submersible Simulation Operation System V1.0" and incorporating cognitive training with VTS. The results indicate that simulated operations significantly affect ergonomic indices, while cognitive training effectively improves physiological indicators and enhances task performance. Based on the findings, future research could be further advanced in the following aspects: (1) Extending the training duration to explore the long-term effects of cognitive training on ergonomic indices and task performance; (2) Investigating the impact of multitasking demands in actual submersible operations on ergonomic indices; (3) Expanding the sample size to analyze the differential effects of individual characteristics such as age, gender, and experience on training outcomes and ergonomic indices; (4) Integrating virtual reality technology to enhance training realism and evaluation validity; (5) Addressing physiological and psychological stress during deep-sea operations and developing recovery strategies to optimize the adaptability of submersible operators; (6) Strengthening interdisciplinary collaboration in psychology, physiology, and engineering to optimize training strategies and ergonomic evaluation from a multidimensional perspective.

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