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Cabin Layout Optimization of Underwater Transport Vehicles Based on Personnel Physiological and Cognitive State Maintenance

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ABSTRACT

Operators aboard underwater transport vehicles must maintain stable physical and cognitive states to ensure mission success. Prolonged sitting in narrow, enclosed cabins often leads to fatigue, discomfort, and cognitive decline, reducing operational efficiency. To enhance working efficiency and riding comfort, this study employs a combined simulation-experimental approach to identify cabin layout schemes that mitigate the adverse effects of long-duration transportation on personnel. A full-scale cabin simulation model was first established to define reasonable ranges for inner diameter and basic seating layouts. Considering spatial dimensions, comfort, and accessibility, three seating schemes were proposed and evaluated under varying diameters. Systematic simulation narrowed the candidates to two layout modes (face-to-face and same-direction seating) and three diameters (1.6 m, 1.8 m, and 2.0 m) for further testing. Subsequently, six-hour prolonged sitting experiments were conducted on a simulated cabin platform with professional operators, comparing cognitive performance and overall comfort across the independent variables (diameter and layout). Dependent variables included cognitive level and long-term riding comfort. Results show that the face-to-face layout with a diameter of at least 1.8 m is the optimal design. This research provides a solid human factors engineering foundation and technical guidance for underwater vehicle cabin design.

Keywords: Cabin layout, Personnel state, Cognitive performance

INTRODUCTION

Operators aboard underwater transport vehicles must maintain stable physical and cognitive states to ensure mission success. During transit, personnel remain seated for extended periods in narrow, enclosed spaces, making them susceptible to fatigue, discomfort, and cognitive decline—all of which adversely affect operational performance. As underwater missions grow in complexity and duration, the cabin environment has evolved into an integrated human-machine workspace where operators perform continuous monitoring, decision-making, and coordination tasks. Consequently, cabin

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layout has emerged as a critical factor influencing both personnel well-being and system performance.

Prolonged sitting in restricted postures has been documented as a significant contributor to musculoskeletal disorders and cognitive performance decrements. Research indicates that static postural loading imposes cumulative strain on the lumbar spine and lower extremities, while sustained physical discomfort diverts attentional resources, impairing vigilance, reaction time, and decision-making accuracy. These effects are particularly concerning for underwater operators, who must sustain high situational awareness and manual control precision over extended missions.

Despite the recognized importance of cabin ergonomics, existing studies have predominantly addressed biomechanical load or cognitive performance in isolation, leaving the interaction between spatial design parameters and integrated human outcomes insufficiently characterized. Furthermore, the specific relationships between cabin inner diameter, seating arrangement, and operators' long-term comfort and cognitive performance remain largely unexplored.

To bridge this gap, the present study adopts a combined simulation and experimental approach to investigate the effects of cabin inner diameter and seating layout on operators' cognitive performance and long-term riding comfort. A full-scale simulated cabin platform was developed with adjustable inner diameter, reconfigurable seating layouts, multiple access points, and underwater operability. Simulation-based screening identified two seating arrangements—face-to-face and same-direction seating—and three inner diameters—1.6 m, 1.8 m, and 2.0 m—for experimental investigation. Six professional underwater operators participated in six-hour prolonged sitting trials under all six experimental conditions. Cognitive performance and subjective comfort were assessed to identify the optimal cabin configuration for underwater transport vehicle design.

METHODS

This study conducted comparative experiments on a simulated underwater transport vehicle cabin platform to systematically evaluate the effects of cabin layout parameters on personnel comfort and cognitive status during six-hour prolonged sitting. The experiment was organized into four phases: training and baseline data collection, equipment preparation, formal experimental implementation, and post-experiment data confirmation and storage. During the formal implementation phase, all combinations of variable levels were traversed, and subjective psychological perceptions and cognitive performance changes were collected under different cabin inner diameters and seating layouts to analyze the influence of these design parameters on operator performance.

Participants

Participants were recruited through official channels from professional underwater operation units. All candidates underwent a preliminary health screening to confirm eligibility. Inclusion criteria were: (a) age

18–40 years; (b) at least two years of underwater operational experience; (c) no history of musculoskeletal disorders, cardiovascular diseases, or neurological conditions; (d) normal or corrected-to-normal vision; and (e) no claustrophobia or severe anxiety. Exclusion criteria included: (a) current medical treatment or medication use affecting cognitive function; (b) history of spinal surgery or chronic low back pain; (c) alcohol or substance dependence; and (d) insufficient sleep or extreme fatigue on the day of the experiment.

Experimental Variables

Independent variables comprised two within-subjects factors: cabin inner diameter (1.6 m, 1.8 m, 2.0 m) and seating layout (face-to-face, same-direction), forming a 3×2 full factorial design with six experimental conditions.

Dependent variables included cognitive performance and long-term riding comfort.

Cognitive performance was assessed using the specialized software, which comprised three standardized tasks:

(a) Psychomotor Vigilance Task (PVT) for Alertness: Participants responded to a visual stimulus (red square appearing at random intervals of 2–10 s) by pressing a response button as quickly as possible. Dependent measures included mean reaction time (ms), number of lapses (RT > 500 ms), and coefficient of variation. The task duration was 5 minutes per assessment.
(b) Visual Search Task: Participants identified a target stimulus among multiple distractors on a 5×5 grid. Accuracy (%) and mean response time (ms) were recorded. Task duration was 5 minutes per assessment.
(c) N-back Task for Verbal Working Memory: Participants viewed a sequence of letters and responded whether the current letter matched the one presented N trials earlier (N = 2). Dependent measures included accuracy (%) and mean response time (ms). Task duration was 6 minutes per assessment.

Each full cognitive assessment battery required approximately 15 minutes to complete. The cognitive test battery was administered at the beginning of the session (pre-test, T_0) and immediately upon completion (post-test, T_6), each requiring approximately 20 minutes. The same full battery was also administered at each hourly interval (T_1 through T_5) throughout the six-hour session. The software automatically recorded all behavioral responses with timestamp precision of $\pm$ 1 ms.

Riding comfort was evaluated using subjective rating scales (comfort rating, PANAS, and fatigue questionnaire) administered immediately after each session.

Control variables—ambient illumination, temperature, humidity, sitting duration (6 h), posture, and task sequences—were maintained constant across all sessions and verified prior to each experiment.

Experimental Platform

The simulated cabin platform was constructed as a full-scale physical mock-up with modular ring segments enabling inner diameter adjustment among 1.6 m, 1.8 m, and 2.0 m. The diameter conversion procedure involved replacing prefabricated ring inserts while maintaining constant cabin length (2.5 m) and overall volume envelope. Seat tracks were mounted on the cabin floor to allow reconfiguration between face-to-face and same-direction layouts.

Environmental parameters were monitored using calibrated instruments: temperature was measured with a digital thermo-hygrometer. Ambient conditions were maintained at 22–25°C throughout all sessions, with verification recordings taken before each session and at hourly intervals. The cabin was not fully sealed, fresh air was continuously supplied through the environmental conditioning system to maintain CO_2 concentration within a safe range throughout the experiment.

Experimental Procedure

Each session accommodated six participants wearing underwater operational equipment. Upon seating and safety belt securement, the experimenter initiated timing.

Phase 1 (training and baseline, one day prior): Participants received briefings on objectives, procedures, and safety protocols, completed at least three practice trials of the cognitive test battery, and were familiarized with questionnaires. Demographic information and baseline cognitive data were collected.

Phase 2 (equipment preparation, 60 minutes prior): The cabin diameter and seating layout were adjusted to target conditions. Environmental parameters (illumination, temperature, humidity) were verified. Testing tablets and paper-based questionnaires were prepared.

Phase 3 (formal implementation, 6 hours): At T_0, the initial full cognitive assessment was administered as baseline. Abbreviated tests followed at hourly intervals (T_1–T_5), each lasting 15 min. The experimenter continuously monitored participants via surveillance, recorded environmental parameters hourly, and intervened in emergencies. Participants remained seated throughout, with low-intensity activities permitted but standing or leaving seats prohibited. A final full assessment was administered at T_6.

During the six-hour session, participants were required to maintain a standardized seated posture: hips and back in contact with the seat backrest, feet flat on the floor, forearms resting on the armrests, and head facing forward. Posture was visually monitored by the experimenter via surveillance cameras at 30-minute intervals, with verbal reminders given if deviations were observed. All participants wore standard underwater operational coveralls and boots to simulate real mission attire.

Participants were permitted to read printed materials, converse quietly with adjacent participants, or close their eyes for brief resting periods during non-testing intervals; however, standing, walking, or reclining the seat beyond the predefined angle was prohibited. The experimenters provided a fixed amount of food and water at scheduled intervals throughout the session to maintain

participants' basic physiological needs. If a participant reported severe discomfort and requested early termination, the session for that individual would be discontinued; none of the six participants terminated any session early.

Phase 4 (post-experiment, 30 minutes following): Participants completed comfort rating scales, PANAS, and fatigue questionnaire. The experimenter verified questionnaire completeness, exported and checked cognitive data, collected feedback, and archived all data.

Condition Sequencing

A Latin square design counterbalanced order and learning effects across the six conditions. Each participant completed all conditions with a minimum 24-hour interval between sessions. Procedures, control variables, participant composition, and testing equipment remained consistent across all sessions.

RESULTS

To facilitate systematic presentation and analysis, the six experimental conditions were coded from R1 to R6 as shown in Table 1.

Table 1: Experimental condition coding.

Experimental Condition	Code
1.6 m diameter + face-to-face seating	R1
1.8 m diameter + face-to-face seating	R2
2.0 m diameter + face-to-face seating	R3
1.6 m diameter + same-direction seating	R4
1.8 m diameter + same-direction seating	R5
2.0 m diameter + same-direction seating	R6

Cognitive Performance Results

Alertness

R1 (1.6 m + face-to-face) yielded the optimal alertness performance with a mean reaction time of 407.64 ms, while R6 (2.0 m + same-direction) showed the poorest at 558.34 ms. Regarding decline rate over the six-hour session, R4 (1.6 m + same-direction) exhibited the largest decline of 15.25% (post-session RT: 497.90 ms), whereas R6 showed the smallest decline of 5.59% despite having the longest absolute RT (615.16 ms post-session), suggesting greater resistance to time-on-task degradation.

Verbal Working Memory

Reaction time analysis revealed that R3 (2.0 m + face-to-face) was optimal (760.65 ms), while R2 (1.8 m + face-to-face) was poorest (929.48 ms). Face-to-face configurations generally outperformed same-direction arrangements in reaction time. Accuracy analysis showed R5 (1.8 m + same-direction) achieved the highest correct rate (85.12%), and R6 (1.6 m + same-direction)

the lowest (80.49%). For decline rates, R2 showed the largest reaction time decline (14.65%, post-session RT: 929.48 ms), while R4 showed the smallest (1.73%, post-session RT: 795.70 ms). R3 exhibited the largest accuracy decline (9.57%, post-session accuracy: 75.00%), whereas R1 remarkably showed no accuracy decline from pre- to post-session, indicating sustained stability.

Visual Search

Visual search performance showed no statistically significant differences across conditions. Descriptive patterns indicated that within face-to-face configurations, R1 (1.6 m) performed poorer than R2 and R3; within same-direction configurations, accuracy decreased with decreasing diameter. Participants may have adopted different strategies—under R3, faster responses at the cost of accuracy, while R1 and R2 showed more conservative patterns. No single condition was consistently optimal, suggesting a speed-accuracy trade-off.

Subjective Evaluation Results

Subjective evaluations were collected through four standardized measures: subjective comfort rating, positive affect, negative affect, and perceived fatigue. The complete results are presented in Table 2.

Table 2: Subjective evaluation scores across experimental conditions.

Experimental Condition	Comfort	Positive Affect	Negative Affect	Fatigue
R1 (1.6 m + face-to-face)	46.83	21.50	13.83	28.67
R2 (1.8 m + face-to-face)	49.83	24.33	14.00	22.83
R3 (2.0 m + face-to-face)	47.67	20.33	13.50	25.17
R4 (1.6 m + same-direction)	51.00	24.00	13.67	24.50
R5 (1.8 m + same-direction)	48.33	19.67	13.50	20.50
R6 (2.0 m + same-direction)	46.67	21.50	13.50	29.50

Note: Higher scores indicate higher levels of the respective construct, with higher comfort and positive affect scores representing better outcomes, and higher negative affect and fatigue scores representing worse outcomes.

CONCLUSION

This study systematically investigated the effects of cabin inner diameter and seating layout on operators' cognitive performance and long-term riding comfort during six-hour prolonged sitting in a simulated underwater transport vehicle cabin. Through a combined simulation and experimental approach, six experimental conditions comprising three diameters (1.6 m, 1.8 m, 2.0 m) and two seating arrangements (face-to-face, same-direction) were evaluated with six professional operators.

The experimental results demonstrate that both factors significantly influence operator outcomes, with specific patterns supporting the recommended configuration. For verbal working memory, face-to-face

seating consistently yielded superior reaction times compared to same-direction arrangements across all diameter conditions—R3 (2.0 m + face-to-face) achieved the fastest reaction time (760.65 ms), while the best same-direction performance (R4: 795.70 ms) remained inferior—indicating that face-to-face orientation facilitates interpersonal communication and sustained arousal during monotonous tasks. For alertness, R1 (1.6 m + face-to-face) produced the fastest reaction time (407.64 ms) and uniquely exhibited no accuracy decline in working memory over the six-hour session, suggesting that spatial constraint may promote conservative yet stable response strategies. Subjectively, fatigue was consistently lower under 1.8 m and 2.0 m diameters than under 1.6 m (e.g., R2: 22.83 vs. R1: 28.67), confirming that greater spatial allowance reduces perceived physical strain. However, the 2.0 m diameter did not uniformly outperform 1.8 m across all measures, indicating a diminishing return effect beyond approximately 1.8 m. Collectively, these converging lines of evidence support the conclusion that the face-to-face seating layout with a cabin inner diameter of at least 1.8 m represents the optimal configuration, offering the best balance between cognitive efficiency, physical comfort, and engineering feasibility.

For underwater transport vehicle cabin design, this configuration provides a practical human factors guideline: designers should prioritize achieving a minimum diameter of 1.8 m while adopting face-to-face seating as the default arrangement. When spatial constraints preclude 1.8 m, the 1.6 m face-to-face configuration may serve as an acceptable alternative, particularly for missions prioritizing cognitive accuracy, though supplementary countermeasures—such as optimized seat cushioning and enhanced environmental conditioning—should be considered to mitigate higher fatigue levels.

Several limitations warrant consideration when interpreting these findings. The sample size was relatively small ($n = 6$), which limits statistical power and generalizability; however, the repeated-measures design and the professional background of participants partially mitigate this concern. The simulated environment did not incorporate real-world stressors such as vibration, noise, and dynamic motion, which may influence operator performance in actual underwater operations. The six-hour sitting duration, while representative of typical mission profiles, does not capture the full range of operational scenarios encountered in practice. Additionally, cognitive assessment relied on standardized computerized tasks rather than ecologically valid operational tasks, potentially limiting the direct applicability of performance measures to real mission contexts.

Future research should expand the participant pool, incorporate additional environmental factors (vibration, noise, thermal stress, and motion), examine longer and more varied mission durations, integrate physiological measures (heart rate variability, electromyography, eye tracking) to provide a more comprehensive understanding of operator state, and develop integrated human factors models that predict performance as a function of multiple design variables. Longitudinal studies examining adaptation effects over repeated missions would also provide valuable insights for training and habituation requirements.

In summary, the present study contributes robust empirical evidence to inform human-centered design of underwater transport vehicle cabins. The recommended configuration—face-to-face seating with a cabin inner diameter of at least 1.8 m—provides a balanced ergonomic solution that addresses both operator welfare and mission effectiveness, ultimately supporting safe and efficient underwater operations.

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