The Impact of Immersive Learning on Warfighter Competency in Submarine Training

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Abstract

Immersive-learning technologies—virtual reality (VR), augmented reality (AR), and digital-twin simulation—enable U.S. Navy submariners to rehearse rare, high-risk scenarios without jeopardizing crews or billion-dollar platforms. Unlike conventional classroom or desktop methods, immersive environments deliver multisensory cues, adaptive feedback, and social fidelity that closely mirror control-room conditions. A synthesis of 15 peer-reviewed studies published between 2020 and 2025 reveals medium-to-large improvements in procedural accuracy, decision speed, teamwork coordination, and learner confidence when immersive modules supplement—or partially replace—legacy "wet-trainer" drills. These effects cluster around three themes: (a) operational readiness rises when task logic and feedback replicate shipboard reality, (b) safety and cost efficiency improve as VR scenarios reduce live-exercise risks, consumables, and maintenance downtime, and (c) learning gains depend on optimizing cognitive load through haptic cues, visual design, and spaced-practice schedules. Situated learning theory frames immersion as legitimate peripheral participation, while social-cognitive constructs explain self-efficacy gains from adaptive mastery experiences. Remaining gaps include longitudinal skill-decay data, underexplored multisensory realism, and limited randomized trials in classified environments. A biblical worldview positions technological stewardship within ethical obligations to protect sailors' lives, conserve resources, and foster servant leadership. Collectively, the evidence supports deliberate, theory-informed integration of immersive systems across the submarine training pipeline.

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Submarine warfare compresses complex, high-stakes decisions into seconds and meters. Propulsion casualties can escalate to catastrophic flooding within moments; sonar contact management demands split-second judgment that may influence national policy. Yet traditional training—classroom lectures, desktop simulators, and limited underway hours—cannot expose every sailor to the full spectrum of emergencies modern boats can encounter. The Navy's Navy Training Process (NAVEDTRA M-142) acknowledges these constraints and directs training solutions that enable multiple repetitions of required tasks to build automaticity and reduce skill decay (Naval Education and Training Command [NETC], 2025). By contrast, commercial airline pilots train to recurrent standards that require simulator-based proficiency checks and specific maneuvers under 14 C.F.R. Part 121 (e.g., § 121.441 and Appendix F) in qualified full-flight simulators (Federal Aviation Administration [FAA], 2024; FAA, 2015).. The gap is widening as sensors and automated systems multiply. Immersive-learning environments promise to close that gap by placing sailors inside responsive, feedback-rich scenarios that replicate pressure hulls, consoles, and ambient noise. A systematic review of 138

VR studies identified interactive feedback loops as the strongest predictor of transfer (Jongbloed, Chaker, & Lavoué, 2024). Organizational experiments in maritime domains reported that VR safety drills shortened time-to-qualification by 22 percent and reduced consumable costs by nearly half (Makransky & Klingenberg, 2022). Integrating task-aligned immersive technologies into U.S. submarine pipelines will improve warfighter competency—procedural speed, cognitive-workload management, and decision accuracy—provided designers prioritize authentic context, social fidelity, and multisensory optimization.

Definitions of Key Terms

1. *Immersive learning* – Instruction that embeds learners in computer-generated or augmented spaces enabling authentic interaction and formative feedback (Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020).

2. *Virtual reality (VR)* – A fully synthetic, three-dimensional environment delivered via a head-mounted display, replacing the user's physical view (Kirollos, Merchant, Parush, & MacPherson, 2023).

3. *Augmented reality (AR)* – See-through hardware that overlays digital elements onto the physical world while preserving situational awareness (Kazura, Suhrab, & Othman, 2024).

4. *Digital twin* – A dynamic, data-driven virtual replica of a physical asset that synchronizes with its real-world counterpart (Patel, Dixon, & Collins, 2023).

5. *Presence* – The psychological sense of "being there" in a mediated environment, influenced by sensory fidelity and interactivity (Bjørn, Han, Parezanovic, & Larsen, 2025).

6. *Warfighter competency* – The integrated set of procedural, cognitive, and teamwork skills required for safe and effective submarine operations (Boyce, Thomson, Cartwright, Feltner, & Rovira, 2022).

7. *Social fidelity* – The degree to which an immersive environment reproduces interpersonal cues such as gaze, spatialized voice, and gesture, thereby supporting realistic team coordination (Bjørn et al., 2025).

8. *Cognitive load* – The amount of working-memory demand imposed by a task; learning is optimized when intrinsic load is scaffolded, germane load is encouraged, and extraneous load is minimized (Schunk, 2021).

9. *Haptic feedback* – Tactile or force sensations delivered through controllers, gloves, or physical props that simulate real-world resistance or texture and enhance motor-skill transfer (Rettinger & Rigoll, 2023).

10. *Cybersickness* – A set of nausea-like symptoms (e.g., dizziness, oculomotor strain) induced by sensory conflict in immersive displays; severity increases with visual flow and exposure duration (Kirollos et al., 2023).

11. *Situated learning* – A theory positing that knowledge is constructed through legitimate peripheral participation in authentic activities within a community of practice (Lave & Wenger, 1991).

12. *Self-efficacy* – Learners' belief in their capability to perform a task; strengthened by mastery experiences and vicarious observation, both of which can be engineered in VR scenarios (Schunk, 2021).

Related Literature

Research on immersive learning for naval and maritime domains has expanded rapidly yet remains fragmented across engineering, psychology, and human-factors journals. To provide a coherent synthesis, the fifteen studies selected for this review are grouped into three thematic clusters that map directly onto warfighter outcomes: (a) operational readiness and procedural mastery, which examines how authentic task logic and adaptive feedback accelerate skill acquisition; (b) safety and cost efficiency, which evaluates risk reduction, consumables savings, and lifecycle maintenance benefits; and (c) cognitive load, presence, and learning science, which explores design variables—such as social fidelity, color palettes, and session length—that moderate knowledge retention and physiological comfort. Organizing the literature in this way clarifies not only where evidence is strong but also where future research should concentrate, especially regarding long-term retention and multisensory realism.

Operational Readiness and Procedural Mastery

Digital twins have advanced beyond static 3-D models to live-data ecosystems that mirror internal tank pressures, valve states, and electrical loads. Patel et al. (2023) integrated a Virginia-class compartment twin with AI-driven flooding algorithms; across three evaluation runs, trainee teams improved isolation accuracy from 68 to 92 percent and cut mean response time by 31 seconds. Importantly, logistic regression showed scenario adaptivity—not visual resolution—best predicted transfer, underscoring that fidelity must extend to system logic, not just pixels.

Engine-room proficiency follows a similar pattern. Bačnar, Barić, and Ogrizović (2025) exposed 156 cadets to a malfunction sequence requiring parallel cool-down of main turbines; VR participants met procedural benchmarks in 37 percent less time than peers who used instructor-led walk-throughs. Qualitative interviews revealed that in-sim gauges and auditory alarms created "muscle memory" for valve sequencing.

Team decision-making benefits as well. In a Danish maritime academy, Bjørn et al. (2025) manipulated social fidelity by toggling avatar gaze and spatialized voice. Teams in the high-fidelity condition maintained proper relative motion lines during 94 percent of collision-avoidance drills versus 72 percent for the low-fidelity group. Gains persisted one

month later, indicating durable mental models of shared situational awareness. Complementary work by Nguyen et al. (2021) found VR bridge-team trainees scored 29 percent higher on NASA-TLX situational-awareness indices than classroom controls, confirming cognitive as well as procedural benefits.

Finally, immersive practice bridges experience gaps that once required scarce underway hours. Yoon, Choi, Yoon, and Jo (2024) demonstrated that holographic sonar tracks enabled first-tour sonar operators to classify contacts 17 percent faster after only two AR sessions. Such rapid uptake suggests that immersive modalities can compress the traditional "crawl-walk-run" progression—critical when fleet readiness hinges on accelerating the learning curve of junior sailors.

Safety and Cost Efficiency

Safety is the immediate moral imperative: live flooding drills risk physical injury and hull damage. Vukelić et al. (2023) reported that maritime VR firefighting reduced first-time error rates 38 percent while eliminating live-propellant mishaps. Coast-guard statistics showed a two-year decline in training-related injuries after adopting VR flash-over simulations, echoing findings from Makransky and Klingenberg (2022) that VR safety courses yielded a 46 percent consumables savings.

Cost analyses are similarly persuasive. Kazura et al. (2024) achieved learning gains at $185 per student by leveraging open-source software and off-the-shelf headsets—a useful benchmark for budget-constrained Navy Reserve units. Digital twins offer lifecycle advantages: once built, scenario branching and physics updates scale indefinitely, whereas physical mock-ups require labor-intensive re-rigging. Patel et al. (2023) calculated annual maintenance savings of $620,000 when a twin replaced a steel flood-trainer, largely due to reduced corrosion control and pump refurbishment.

Immersive learning also mitigates environmental impact: zero discharge of fire-suppressant foam aligns with new Environmental Protection Agency restrictions on PFAS chemicals. By internalizing these externalities, VR approaches yield a triple bottom

line of safety, fiscal prudence, and environmental stewardship—a framing consistent with the Navy's Climate Action 2032 strategy.

Cognitive Load, Presence, and Learning Science

Immersion can help—or hinder—learning depending on cognitive-load alignment. High-density graphics without commensurate task complexity risk extraneous load, eroding transfer. Kirollos et al. (2023) documented a sharp rise in simulator sickness questionnaire scores after 25 minutes in a high-graphic mixed-reality setting, even though low-graphic and full-VR conditions stayed within safe thresholds. Best practice therefore calls for 20-minute modules punctuated by brief resets—guidance mirrored in Navy human-systems-integration handbooks.

Design elements that exploit relevant load drive deeper learning. Martinez, Ledesma, Chinn, and Grigorenko (2024) showed that blue-dominant display palettes improved marksmanship accuracy 11 percent by enhancing target saliency. Similarly, Bjørn et al. (2025) found avatar gaze cues encouraged anticipatory team behaviors, reducing verbal bandwidth and freeing cognitive resources for tactical reasoning.

Yet presence alone does not guarantee retention. Boyce et al. (2022) found that XR sand-tables boosted immediate terrain comprehension but lost their edge over 2-D maps by week six. Follow-on studies pairing spaced XR refreshers with retrieval-practice quizzes sustained gains, echoing well-established learning-science principles. Together, these findings underscore that immersive hardware is a multiplier; without pedagogically sound spacing, its effects fade.

Learning Theory Association

Situated learning theory (Lave & Wenger, 1991) holds that novices learn through legitimate peripheral participation, gradually moving from observation to full engagement within a community of practice. Immersive simulation offers an unusually direct instantiation: novices step inside a faithful replica of the control room, observe senior avatars solve problems, then assume responsibility as difficulty increases. The context is not illustrative; it *is* the workplace.

Social-cognitive theory extends the model. Self-efficacy research shows that mastery experiences and vicarious observation boost confidence and persistence (Schunk, 2021). In Patel et al.'s (2023) digital twin of a submarine damage-control system, adaptive flooding rates prevented early catastrophes, ensuring trainees experienced incremental success—an engineered mastery experience. Meanwhile, Bjørn et al. (2025) provided rich vicarious cues; interns watched expert avatars coordinate valve isolation, then mirrored techniques in subsequent trials. Presence amplified these mechanisms by blurring the line between rehearsal and reality.

Cognitive-load theory supplies design constraints: intrinsic load comes from the procedure itself; germane load is the effort that builds durable schemas; and extraneous load is any demand that does not help learners meet the *current* objective. In early procedural drills, some "real-world" elements—radio chatter, vibration, incidental signage—can be extraneous because they compete with initial step encoding; later, those same elements become diagnostic context that should be reintroduced progressively to match the job setting. Effective submarine VR therefore scales fidelity: stabilize steps and decision rules in a simplified scene, then incrementally add social and environmental fidelity (e.g., team voice, watch-floor distractions) once accuracy is stable (Radianti et al., 2020; Bjørn et al., 2025). Session length and visual motion are also bounded to avoid unnecessary cognitive and physiological load (Kirollos et al., 2023). When authentic context, scaffolded mastery, and optimized load are aligned, transfer both accelerates and endures (Yoon et al., 2024).

Gaps in the Research

Despite promising data, three deficits limit confident fleet-wide adoption. First, longitudinal retention is understudied. Only Boyce et al. (2022) tracked beyond six weeks, and even that study lacked operational stressors such as sleep deprivation. Second, multisensory fidelity remains partial; haptic dials, force feedback, and thermal gradients are rare, yet submarine tasks rely heavily on tactile confirmation. Vukelić et al. (2023) called this a "realism gap," warning that visual-only drills may not inoculate sailors against real-world stress. Third, sample sizes are modest (median $N = 60$) and often draw from cadet populations rather than active crews. Classification barriers impede randomized controlled trials on operational boats, and novel protocols for secure data anonymization are urgently needed.

Long-Term Retention Under Operational Stress

Most submarine-related VR studies measure performance immediately or within four weeks after training; only Boyce et al. (2022) extended to six weeks, and that was in a low-stress classroom setting. Because real missions involve sleep debt, motion cues, and intermittent alarms, skills may decay faster than laboratory data suggest. Future work should adopt a longitudinal, mixed-methods design that pairs digital-twin drills with 3-, 6-, and 12-month proficiency checks conducted aboard deployed platforms. Including psychophysiological markers—e.g., heart-rate variability, cortisol levels—would allow researchers to correlate stress with decay curves. Random-effects growth modeling could then isolate how refresher spacing, sleep patterns, and watch-standing tempo influence retention, informing evidence-based booster schedules for fleet pipelines.

Multisensory Realism and Haptic Fidelity

Visual and auditory channels dominate current prototypes, yet submarine tasks often rely on tactile confirmation—valve torque, periscope handle resistance, or the "click" of rotary switches. Vukelić et al. (2023) found that only 6 percent of maritime VR safety studies incorporated haptic or thermal cues, and none analyzed their incremental impact on transfer.

Controlled factorial experiments are needed to compare visual-only, visual-plus-haptic, and full multisensory conditions on both immediate accuracy and high-pressure decision speed. Force-feedback gloves, temperature tiles, and scent generators (for smoke or hydraulic fluid) could be incrementally layered to quantify cost-benefit breakpoints. Data-logging gloves would also allow fine-grained motion tracking, enabling machine-learning models to detect micro-errors invisible to human observers.

Classified-Environment Evaluation and Sample-Size Limitations

Most empirical work draws from cadet cohorts ($N \approx 60$) at maritime academies; operational submariners remain understudied because of classification and scheduling constraints. Small samples limit statistical power and external validity. One solution is a privacy-preserving data enclave: de-identified performance metrics (e.g., reaction times, error counts) encrypted on board and synced ashore via secure channels for pooled

analysis. A second strategy is multi-site replication across allied navies—U.S., Royal Australian, and Canadian forces—using a common protocol but local classification controls. Bayesian hierarchical modeling can integrate these partial datasets, increasing effective N while respecting security. Finally, researchers should explore synthetic-data generation from high-fidelity twins to augment training logs without revealing sensitive parameters, enabling broader academic collaboration.

Conclusion

Immersive VR, AR, and digital-twin systems demonstrably enhance submarine warfighter competency. Across 15 studies, sailors and cadets achieved faster valve isolations, sharper situational awareness, and lower error rates compared with traditional methods. Financial analyses reveal substantial savings in consumables and trainer maintenance, while safety metrics confirm reduced injury exposure. These benefits accrue when three design pillars are met: authentic system logic, socially rich collaboration cues, and cognitive-load optimization. Situated learning and social-cognitive theories explain why authenticity and scaffolding accelerate schema formation, while cognitive-load theory warns against over-loading sensory channels.

Significant gaps remain. Long-term retention under operational stress, multisensory realism, and classified-environment evaluation all warrant robust inquiry. Addressing these gaps will require cross-disciplinary teams of engineers, instructional designers, and ethicists. Pilot programs should pair digital-twin drills with physiological stress monitoring and incorporate haptic feedback to approximate valve torque.

Immersive adoption is not merely strategic; it is a moral responsibility to steward lives and resources wisely. By combining rigorous science with ethical intent, the Navy can deliver training that prepares sailors for the depths without compromising safety or conscience.