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The Effectiveness of Simulation-Based Learning in Improving Maritime Operational Skills and Decision-Making

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Abstract

Maritime safety depends on the operational skills and decision-making of seafarers, yet traditional training based on classroom teaching and sea time offers limited exposure to rare, high-risk events. This article examines the effectiveness of simulation-based learning as a means of improving maritime operational skills and decision-making. Drawing on experiential learning theory, cognitive load theory, naturalistic decision-making research and the regulatory framework of the International Maritime Organization, it synthesises evidence on how simulation supports technical skill acquisition, situation awareness, teamwork and assessment. The analysis shows that simulation is most effective when fidelity is matched to learning objectives, when scenarios are progressively structured, when instructors are well prepared and when structured debriefing is used to convert experience into understanding. The article also identifies limitations, including cost, fidelity gaps, assessment validity and uncertain transfer to real operations, and outlines directions for future research and practice. An illustrative figure summarises the expected competence profiles when simulation supplements conventional training.

Keywords: simulation-based learning, maritime training, decision-making, situation awareness, bridge resource management

INTRODUCTION

Maritime transport carries more than eighty percent of the world's trade by volume, and the safe movement of ships through congested waters, restricted channels and severe weather depends heavily on the competence of the officers and crews who operate them. Despite major advances in navigation technology, human performance continues to be implicated in a large share of collisions, groundings and other casualties. Operational skills such as ship handling, collision avoidance, passage planning and emergency response, together with the decision-making that binds them, therefore remain central concerns for maritime education and training institutions, shipping companies and regulators. Traditional training routes rely on classroom instruction, onboard apprenticeship and sea time. These routes

are valuable but have clear limits. Trainees cannot be exposed deliberately to rare, high-consequence events such as a blackout in a narrow channel, a steering failure during pilotage or a fire in a cargo hold. Opportunities to practise are shaped by the voyages a vessel happens to make rather than by a planned learning sequence, and mistakes made at sea can carry unacceptable cost to life, cargo and the environment. Simulation-based learning has emerged as the principal response to this gap, allowing learners to practise in a controlled, repeatable and safe environment. This article examines the effectiveness of simulation-based learning in improving maritime operational skills and decision-making. It draws on the wider literature on simulation-based training in aviation, healthcare and maritime education, on cognitive and experiential learning theory, and on the regulatory framework of the International Maritime Organization. The article asks how simulation contributes to technical skill acquisition, how it supports situation awareness and judgement under pressure, what instructional conditions make it effective, and what limitations must be managed. The discussion is conceptual and integrative, and the figure presented is an illustrative synthesis rather than a report of new empirical measurements.

Theoretical Foundations of Simulation-Based Learning:

Simulation-based learning is grounded in experiential learning theory, which holds that knowledge is created through a cycle of concrete experience, reflective observation, abstract conceptualisation and active experimentation (Kolb, 1984). A bridge simulator can place a trainee in a concrete experience, such as an overtaking situation in a traffic separation scheme, and the instructor-led debriefing then supports reflection and the formation of general principles that the trainee can test in the next exercise. The cycle is far more compressed than it would be at sea, which is a major source of the efficiency of simulation. Cognitive load theory offers a second foundation. Working memory is limited, and novices who are overwhelmed by the full complexity of a real task often learn little from it (Sweller, 1988). Simulation allows the instructor to reduce or increase complexity deliberately, for example by fixing the weather and traffic density for a first exercise and then adding wind, current, equipment failure and radio traffic as competence grows. This scaffolding aligns task difficulty with the learner's developing capacity and prevents cognitive overload while still providing realistic practice. Naturalistic decision-making research adds a third perspective. Experienced professionals rarely compare options analytically in time-critical situations; instead they recognise patterns, mentally simulate a likely course of action and adopt it if it appears workable (Klein, 1998). Such recognition-based expertise is built through exposure to many varied cases. Simulation can supply this exposure in concentrated form, allowing officers to accumulate a repertoire of scenarios that would take years to encounter at sea. Together, these theories explain why simulation is not merely a substitute for experience but a means of structuring it.

Evolution of Maritime Simulation Technologies:

Maritime simulation began with simple radar and manoeuvring trainers in the mid twentieth century and has evolved into integrated systems that combine full-mission bridge simulators, engine-room simulators, cargo-handling simulators and increasingly immersive virtual reality environments. Modern full-mission bridge simulators reproduce the visual scene, the vessel's hydrodynamic behaviour, the radar and electronic chart display and information system, and the voice communication environment. Several bridges can be linked so that multiple ships interact within the same exercise area, which enables realistic traffic situations and team-based training. Advances in computing power, graphics and mathematical modelling of ship motion have improved fidelity substantially. Hydrodynamic models now represent interaction effects such as bank suction, squat and shallow-water behaviour, and the databases of real ports and waterways allow pilots and masters to rehearse specific arrival and departure operations before they occur. Remote and distributed simulation, in which participants in different locations join a shared exercise, has further widened access, especially for institutions that cannot afford a full-mission facility. More recent developments include head-mounted virtual reality, augmented reality overlays and desktop trainers that reproduce selected tasks at low cost. These tools are not replacements for full-mission simulators but they extend the range of training options, particularly for procedural and familiarisation tasks. The growing diversity of platforms raises an important question for training designers, namely which technology is appropriate for which learning objective, a question that is addressed in the discussion of fidelity later in this article.

Regulatory Framework and Competence Standards:

The regulatory foundation for maritime training is the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers and its associated Code (International Maritime Organization, 2017). The Convention sets minimum competence standards for officers and ratings and, in its amended form, explicitly recognises simulation as an approved method of demonstrating competence and, in defined circumstances, of delivering training. Certain competences, including the use of radar and automatic radar plotting aids, are expected to be demonstrated through simulator-based assessment. The Convention also establishes performance standards for simulation equipment, requiring that simulators be capable of simulating the operational environment realistically, provide behavioural realism appropriate to the exercise, and offer a controlled operating environment that allows a variety of conditions to be created. Instructors are expected to be qualified in the use of the simulator and in the methods of training and

assessment. These provisions give simulation a formal status and set a baseline for quality, while leaving training providers considerable freedom in instructional design. The regulatory emphasis on competence rather than time served is important for the argument of this article. A competence-based approach requires evidence that a trainee can perform a task to a defined standard, and simulation is well suited to generating that evidence because performance can be observed, recorded and compared across trainees under identical conditions. At the same time, compliance with the minimum standard does not guarantee effective learning, and the quality of scenario design, facilitation and assessment still determines whether the regulatory potential of simulation is realised.

Simulation Fidelity and Instructional Design:

Fidelity is often discussed as if more were always better, but research on simulation suggests a more nuanced position. Physical fidelity refers to how closely the equipment resembles the real system, functional fidelity to how closely it behaves like the real system, and psychological fidelity to how closely it evokes the cognitive and emotional demands of the real task. Effective training depends on matching these dimensions to the learning objectives rather than maximising all of them (Hontvedt & Øvergård, 2020). A procedural task may be learned well on a low-cost trainer, whereas a task involving teamwork under stress may require a full-mission environment. Reviews of simulation-based training in other safety-critical fields identify the features that most consistently lead to effective learning. These include feedback during and after practice, repetitive practice, a curriculum that integrates simulation with other instruction, a range of task difficulty, defined outcomes and individualised learning (Issenberg et al., 2005). Meta-analytic evidence from health professions education shows large positive effects of technology-enhanced simulation on knowledge, skills and behaviours compared with no intervention, with the effects strongest when instruction is well designed (Cook et al., 2011). Although the setting differs, the underlying learning mechanisms are closely comparable to those in maritime training. Scenario design is the practical core of instructional design. A well-constructed scenario has explicit learning objectives, a realistic narrative, planned trigger events that elicit the targeted skills, and defined performance indicators for observation. Scenarios that are too easy fail to challenge the trainee, while scenarios that are too complex can encourage random trial and error. Instructors should therefore sequence scenarios progressively and prepare contingency branches so that the exercise can be adapted to the trainee's actual performance without losing its educational purpose.

Development of Technical and Operational Skills:

The most direct contribution of simulation is to the development of technical and operational skills. Ship handling, for example, depends on understanding how a vessel responds to rudder, propulsion, wind and current, and this understanding is acquired through repeated manoeuvring. In a simulator a trainee can berth the same vessel in the same port many times, vary the conditions, observe the consequences of errors and receive immediate feedback, a volume of practice that is impossible at sea. Similar benefits arise for radar plotting, use of electronic charts, bridge equipment operation and engine-room procedures. Simulation is especially valuable for skills whose practice at sea would be dangerous or economically prohibitive. Emergency situations such as loss of steering, propulsion failure, heavy-weather handling, man-overboard recovery and responses to fire can be rehearsed repeatedly without risk. Because the scenario can be paused, replayed and analysed, trainees can see precisely where an action went wrong and what the alternative would have produced. This capacity for controlled exposure to failure transforms errors from catastrophic events into learning opportunities. Evidence from systematic reviews of bridge simulation suggests that simulators are widely accepted as effective for training in navigation and manoeuvring, although rigorous controlled studies with objective performance measures remain less common than descriptive accounts and perception-based evaluations (Sellberg, 2017). The skill development benefit appears greatest when simulation is integrated with onboard experience rather than treated as an isolated event, because trainees can connect what they practised ashore with the demands of real operations. Figure 1 summarises, in illustrative form, the pattern of competence profiles commonly expected when simulation supplements conventional training.

Decision-Making and Situation Awareness:

Decision-making in maritime operations is typically time-pressured, uncertain and dependent on incomplete information. Good decisions rest on accurate situation awareness, which is described as the perception of elements in the environment, the comprehension of their meaning and the projection of their status in the near future (Endsley, 1995). A navigating officer who notices a closing vessel, understands that the encounter will become a risk of collision and anticipates the other ship's likely action is exercising all three levels of awareness. Failures at any level can lead to flawed decisions. Simulation offers a unique environment in which to train these cognitive processes. Scenarios can be designed so that cues are ambiguous, information is delayed, alarms compete for attention or communication with a pilot or another vessel is imperfect, thereby forcing the trainee to prioritise, verify and decide. Because the same scenario can be run with different trainees, instructors can compare how individuals build and lose awareness, and can use freeze-frame techniques to ask what the trainee was attending to and what they expected to happen next. Experience in simulated environments also supports the development of recognition-primed decision-making, because trainees see

many variants of a situation and learn which cues distinguish them. Research on non-technical skills emphasises that decision-making should be trained explicitly rather than assumed to follow from technical knowledge (Flin et al., 2008). Training that combines realistic scenarios with structured reflection on how options were generated and selected helps officers to make better decisions under stress, to recognise when their first judgement may be biased and to adopt a more deliberate approach when time allows.

Teamwork, Communication and Bridge Resource Management:

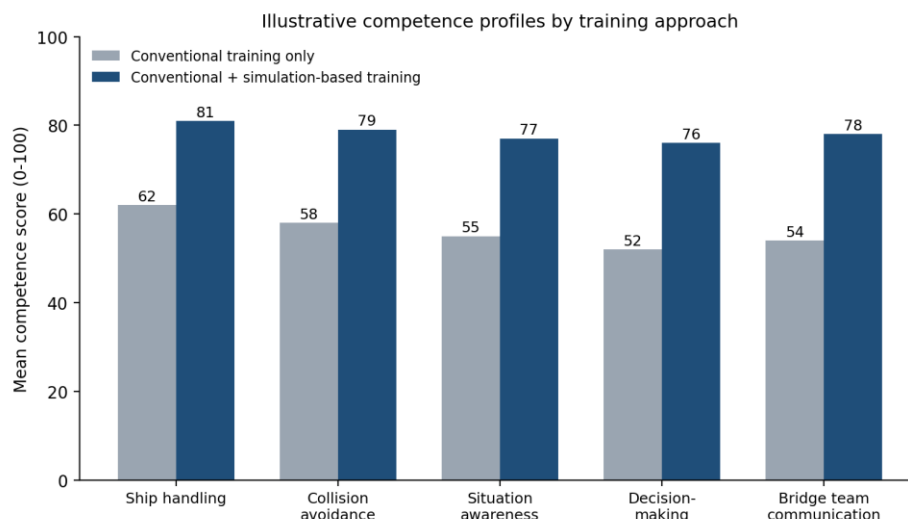
Maritime operations are performed by teams, including the master, officers, pilot, lookouts, helmsman and, increasingly, shore-based support, and many serious accidents have involved breakdowns of communication, shared understanding or authority gradient rather than purely technical failure. Bridge resource management training seeks to improve the way teams plan, allocate tasks, monitor one another, challenge errors and communicate. Simulation provides the natural setting for this training because it brings the whole team together in a realistic environment where interaction can be observed. A well-designed team scenario will create situations in which poor communication has visible consequences, for instance a pilot's instruction that is misunderstood, a helm order repeated incorrectly or a junior officer who hesitates to question a senior decision. The team experiences the effect of the failure within a safe space and can then analyse the sequence of events during debriefing. Standard phraseology, closed-loop communication, assertiveness and cross-checking can be practised until they become habitual, and the recorded audio and video allow behaviours to be reviewed objectively. Cultural and hierarchical factors deserve particular attention in multinational crews. Differences in expectations about authority, speaking up and feedback influence how a team uses its members' knowledge, and simulation allows these differences to be made visible and discussed constructively. The long-term benefit is not only improved performance in a specific exercise but the formation of shared mental models and a safety culture in which questioning and mutual support are regarded as normal professional behaviour.

Assessment, Debriefing and Feedback:

Debriefing is widely regarded as the stage in which most learning from simulation occurs, since it is where experience is converted into understanding. An effective debriefing is structured, non-punitive and focused on the reasons behind actions rather than only on their outcomes. Instructors may use recorded replays, track plots and radar data to reconstruct what happened, ask open questions to explore the trainee's thinking and guide the group to identify principles that can be applied elsewhere. Research on simulator-based bridge training indicates that the quality of facilitation strongly shapes what trainees take from an exercise. Simulation also supports assessment. Because conditions can be standardised, performance can be evaluated against explicit criteria such as distance at closest point of approach, compliance with the collision regulations, accuracy of position monitoring, timeliness of actions and quality of communication. Objective data from the simulator can be combined with observer ratings of non-technical skills to give a fuller picture of competence. This supports both formative assessment, which guides further learning, and summative assessment, which supports certification. Assessment in simulation nonetheless raises concerns about validity and reliability. Instructors may differ in their ratings, scenarios may not represent the full range of real conditions and performance in a simulator may not predict performance at sea. Good practice includes the use of clear rubrics, training and calibration of assessors, multiple scenarios across multiple occasions, and an explicit link between assessed behaviours and the competences required by the regulatory framework. When these conditions are met, assessment through simulation becomes a credible and transparent component of competence-based education.

Challenges, Limitations and Future Directions:

Despite its strengths, simulation-based learning faces several limitations. Full-mission simulators are expensive to acquire, maintain and staff, which limits access in many developing maritime nations and smaller training institutions. Fidelity gaps remain, for instance in the representation of motion cues, fatigue, noise, real weather and the sheer ambiguity of operational life. There is also a risk of negative training if trainees learn to rely on simulator artefacts, or if poorly designed scenarios reward behaviours that would be unsafe at sea. The transfer of learning from simulator to real operations is assumed more often than it is measured. The quality of instruction is a further constraint. Simulators do not teach by themselves, and equipment investment without parallel investment in instructor development produces limited benefit. Instructors need skill in scenario design, facilitation and assessment as well as maritime expertise. Research gaps also persist, including a shortage of longitudinal studies that follow trainees into their careers, and of studies that link simulation-based performance to real incident and near-miss data. Future directions are promising. Artificial intelligence may enable adaptive scenarios and virtual traffic that respond realistically to trainee decisions, and learning analytics can turn simulator logs into detailed performance profiles. Remote and virtual reality platforms may expand access, and the growth of autonomous and remotely supervised ships will create new competence demands, such as supervising automation and intervening when it fails, which simulation is well placed to address. Realising these benefits will require shared standards for scenario quality, validated assessment tools and stronger collaboration between researchers, regulators, industry and training institutions.



Summary:

Simulation-based learning has become an essential element of maritime education and training because it addresses the main limits of traditional approaches: restricted exposure to rare events, the cost of error at sea and the difficulty of structuring practice around a learning plan. The reviewed theory and evidence indicate that simulation improves technical operational skills through repeated, safe and feedback-rich practice, strengthens situation awareness and recognition-based decision-making through varied scenarios, and develops teamwork and communication through realistic bridge resource management exercises. The effectiveness of simulation does not arise from technology alone. It depends on aligning fidelity with learning objectives, designing progressive and purposeful scenarios, preparing competent instructors, and using structured debriefing and valid assessment. Limitations such as high cost, fidelity gaps, assessor variability and the uncertain transfer of learning to real operations must be actively managed. Future work should prioritise longitudinal and transfer studies, validated assessment instruments and the use of adaptive and immersive technologies, so that simulation continues to raise the competence of seafarers and the safety of shipping.

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