

Augmented Reality Applications for Ship Handling Simulation: Effectiveness Assessment in Nautical Training at Maritime Institute

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ABSTRACT

Maritime bridge simulation training represents one of the most pedagogically challenging yet operationally critical components of nautical officer education, tasked with developing complex spatial reasoning, situational awareness, and decision-making competencies required for safe ship navigation. Traditional bridge simulators generate a "realism gap" between simulation training and actual shipboard practice, as virtual environments remain perceptibly artificial and cannot fully replicate the embodied experience of shipboard watchkeeping. Augmented Reality (AR) technology offers a fundamentally different approach through hybrid physical-digital learning environments that preserve physical training spaces while selectively augmenting them with digital information and navigational overlays. This study investigates AR-enhanced ship handling simulation effectiveness at STIP Jakarta through mixed-methods assessment involving 120 nautical cadets and 18 simulator instructors. Quantitative findings reveal AR training significantly improves spatial awareness by 31.4 percent, collision avoidance decision-making by 26.3 percent, and overall nautical competency by 27.8 percent relative to traditional simulation, with greatest improvements in complex restricted visibility and emergency scenarios. Qualitative analysis identified immediate spatial comprehension and scaffolded complexity reduction as key pedagogical mechanisms. The study proposes an AR Maritime Simulation Integration Framework incorporating position overlay systems, collision warning applications, environmental condition simulation, and instructor training for AR-mediated pedagogy.

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1. INTRODUCTION

Maritime bridge simulation training represents one of the most pedagogically challenging yet operationally critical components of nautical officer education, tasked with developing the extraordinarily complex spatial reasoning abilities, multifaceted situational awareness capacities, and sophisticated decision-making competencies required for safe ship navigation in diverse operational contexts through carefully controlled training experiences that approximate but fundamentally cannot fully replicate the sensory richness, environmental variability, psychological pressure, and kinesthetic feedback of actual shipboard watchkeeping under real operational conditions [1]. The development of competent bridge officers requires not merely theoretical knowledge of navigation rules, chart interpretation, and collision avoidance regulations, but deeply

internalized spatial reasoning skills enabling accurate mental modeling of vessel position and motion dynamics, highly developed situational awareness maintaining continuous comprehension of complex traffic patterns and hazard proximity, and sound judgment under pressure making critical safety decisions with incomplete information and time constraints that characterize real maritime operations.

Traditional bridge simulators—sophisticated computer systems projecting detailed virtual seascapes onto large screens surrounding a carefully constructed mock bridge environment equipped with fully functional radar displays, Electronic Chart Display and Information Systems (ECDIS), engine telegraph controls, steering mechanisms, and communications equipment—have served as the dominant simulation technology platform in maritime education institutions worldwide for several decades, providing trainees with valuable structured exposure to diverse navigation scenarios ranging from routine coastal passages through familiar waters to complex emergency situations such as engine failures occurring in confined waters with heavy traffic, sudden weather deterioration requiring immediate course alterations, or equipment malfunctions demanding backup procedure implementation [2]. These simulation systems enable systematic competency development through scenario repetition impossible aboard actual vessels, provide safe environments for practicing high-risk maneuvers without endangering vessels or crews, allow instructors to introduce precisely controlled emergency situations for training purposes, and offer immediate performance feedback and debriefing opportunities enhancing learning effectiveness.

Yet despite their substantial pedagogical value and widespread adoption across maritime education institutions globally, traditional bridge simulator systems generate what researchers and practitioners increasingly recognize as a fundamental "realism gap" between simulation training experiences and actual shipboard operational practice that potentially limits competency transfer from training environments to real-world performance contexts [1]. The virtual environment projected on simulator screens, however visually sophisticated and technically accurate in its rendering of seascapes, weather conditions, and vessel dynamics, remains perceptibly and fundamentally artificial to trainees who recognize they are viewing computer-generated imagery rather than actual maritime environments. The physical space of the simulation laboratory, despite careful design to approximate bridge layout and equipment positioning, remains obviously a classroom or training facility rather than an actual vessel, lacking the subtle motion cues, vibration feedback, ambient sounds, and environmental conditions that constitute the embodied reality of shipboard watch standing. Most critically, the fundamental embodied experience of standing watch on a moving ship responding dynamically to wind, waves, and current forces in constantly changing weather and sea state conditions cannot be fully replicated through stationary screens, simulated controls, and classroom environments that lack the kinesthetic and vestibular feedback essential to developing the deeply internalized spatial awareness and situational judgment that characterize expert bridge officer performance [3].

Augmented Reality (AR) technology—sophisticated systems that overlay computer-generated visual information, auditory cues, haptic feedback, and interactive digital content onto users' direct perceptual experience of real-world physical environments through head-mounted displays, mobile device screens, spatial projection systems, or other interface mechanisms—offers a fundamentally different and potentially transformative approach to simulation-based training that addresses the realism gap challenge through creation of hybrid physical-digital learning environments that preserve rather than replace authentic physical interaction while strategically augmenting it with digital information, instructional scaffolding, and interactive guidance [2]. Rather than transporting learners entirely into virtual simulation environments that substitute computer-generated imagery for physical reality, AR technology preserves the physical training environment and embodied interaction with real equipment while selectively overlaying digital information, navigational aids, real-time feedback, and instructional content that enhance learning without disconnecting trainees from physical reality.

In AR-enhanced maritime training applications, a nautical cadet practicing collision avoidance maneuvers using AR technology might stand on an actual bridge mock-up equipped with real physical controls and instruments, looking through AR glasses or viewing through tablet displays at an actual physical harbor model or real maritime environment while simultaneously seeing computer-generated digital representations of ship traffic, navigation buoys, depth contours, collision risk zones, and hazard warnings overlaid directly onto the physical scene in real-time alignment with the physical environment, creating a uniquely blended experience that strategically combines the tangible physicality and embodied engagement benefits of real-world interaction with the rich informational content, precise scenario control, immediate feedback capabilities, and instructional scaffolding opportunities that digital simulation systems provide [3]. This hybrid approach fundamentally preserves the cognitive and embodied engagement advantages of physical learning environments while adding the pedagogical enhancement, performance support, and training flexibility that purely digital systems offer but that traditional physical training cannot achieve.

The potential applications of AR technology in maritime training contexts extend across multiple critical competency development domains central to bridge officer professional preparation. For spatial awareness training—developing and maintaining accurate dynamic mental models of vessel position, heading, speed, rate of turn, and proximity to navigational hazards, other traffic, and shallow water—AR systems can overlay real-time position indicators, projected future course lines, turning radius visualizations, closest point of approach calculations, and dynamic safety zone representations directly onto trainees' view of physical navigation charts or three-dimensional harbor models, making inherently abstract spatial relationships tangible and immediately visible in ways that traditional paper chart work or conventional radar display interpretation fundamentally cannot achieve [4]. For collision avoidance decision-making training, AR applications can display target vessel current positions, projected future positions based on observed course and speed, predicted collision points if current courses are maintained, safe passing distances conforming to collision regulations, and real-time risk assessments overlaid directly onto the trainee's field of view during dynamic bridge navigation exercises, providing immediate continuous visual feedback regarding whether proposed maneuver decisions will successfully avoid close-quarters situations or create new hazards requiring further intervention.

For emergency procedure execution training, AR systems can display interactive procedural checklists, real-time system status indicators, step-by-step guidance sequences, equipment location highlighting, and critical parameter monitoring overlaid directly onto actual bridge equipment and control panels, supporting trainees through complex multi-step emergency response sequences without requiring them to divert visual attention from the operational environment to separate paper manuals, wall-mounted procedure cards, or computer screen displays that fragment attention and increase cognitive load during high-stress situations [3]. For weather and environmental condition training, AR technology can simulate realistic fog effects, heavy rain visualization, reduced visibility conditions, or nighttime navigation darkness overlaid onto actual daytime bridge training environments, dramatically expanding the range of environmental scenarios deliverable within training facilities without requiring physical weather condition replication through expensive climate control systems or logistically challenging nighttime training session scheduling that reduces training availability and increases operational costs.

Despite AR technology's substantial and growing adoption across aviation pilot training programs, military tactical simulation systems, surgical procedure training in medical education, and industrial maintenance training applications, its systematic application in maritime training contexts remains surprisingly limited and fragmented, and its pedagogical effectiveness specifically for developing the complex ship handling competencies that constitute the core of bridge officer professional preparation has not been rigorously evaluated through systematic empirical research in maritime education contexts [4]. The small handful of published research studies examining AR applications in maritime-related contexts have focused primarily on marine engineering maintenance training for engine room personnel or basic navigation system familiarization for entry-level students rather than investigating the complex, dynamic ship handling decision-making under realistic operational pressure that constitutes the most critical and pedagogically challenging component of bridge officer competency development requiring the highest levels of spatial reasoning, situational awareness, and professional judgment [3].

STIP Jakarta's recent strategic implementation of AR applications within its comprehensive bridge simulator training program—developed through collaborative partnerships with maritime technology developers and active participation in international maritime education AR pilot initiatives—provides a uniquely valuable empirical context for systematically investigating AR training effectiveness specifically for ship handling skill acquisition within the Indonesian maritime education environment, addressing the critical research gap regarding AR's pedagogical value for the most complex and consequential aspects of nautical officer professional preparation.

This comprehensive study is guided by an integrated central research question: To what extent does AR-enhanced ship handling simulation training improve nautical competency development relative to traditional bridge simulation training approaches at STIP Jakarta, and what specific AR features, interface designs, and pedagogical implementation approaches most effectively leverage AR technology's unique affordances and capabilities for optimizing ship handling skill acquisition across diverse training scenarios and competency domains?

2. RESEARCH METHOD

This study employed a rigorous sequential explanatory mixed-methods research design strategically integrating quantitative survey assessment of AR training effectiveness with qualitative Focus Group Discussions exploring learning experience quality, cognitive process differences, and skill transfer perceptions [5]. The mixed-methods approach enabled comprehensive investigation combining precise measurement of competency development magnitude through statistical analysis with rich contextual understanding of

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pedagogical mechanisms, learning process experiences, and implementation challenges through detailed qualitative inquiry, providing more complete and nuanced understanding than either purely quantitative or purely qualitative approaches could achieve independently [6].

The quantitative survey assessment phase systematically measured student self-assessed competency development perceptions and instructor-assessed skill acquisition outcomes across AR-enhanced and traditional simulation training conditions using validated measurement instruments, enabling direct within-subject comparison of training modality effectiveness while controlling for individual differences in baseline ability, prior experience, and learning aptitude. The qualitative FGD phase generated rich, detailed understanding of how AR technology affects spatial reasoning cognitive processes, decision-making strategy development, and the embodied phenomenological experience of ship handling training, illuminating the psychological and pedagogical mechanisms generating the quantitative effects observed in survey data.

The sequential explanatory design strategically prioritized quantitative competency assessment to establish empirical evidence regarding the magnitude and statistical significance of AR training effects on measurable learning outcomes, followed by carefully designed qualitative FGDs explicitly focused on explaining the pedagogical processes, cognitive mechanisms, technological affordances, and instructional implementation factors generating those quantitatively documented effects. This sequence enables qualitative findings to explain and contextualize quantitative patterns rather than merely supplementing them with anecdotal observations.

The study population comprised two complementary stakeholder groups providing distinct yet interrelated perspectives essential for comprehensive AR training effectiveness assessment. Nautical academy cadets enrolled in STIP Jakarta's nautical science professional preparation program who completed required ship handling training modules delivered in both AR-enhanced and traditional bridge simulator conditions (n = 120 participants) enabled rigorous within-subject comparison of competency development trajectories, learning satisfaction levels, and cognitive load experiences across fundamentally different training modalities while controlling for individual variation. Cadets participating in the study were predominantly in their third and fourth academic years, having successfully completed foundational navigation coursework covering collision regulations, chart interpretation, radar operation, and basic ship handling principles, and possessing substantial baseline bridge simulation experience necessary for informed comparative assessment of training modality differences based on direct experiential knowledge rather than abstract speculation.

Simulator instructors actively teaching ship handling courses at STIP Jakarta who delivered training content in both AR-enhanced and traditional simulation modes (n = 18 experienced maritime educators) provided the essential instructor perspective on pedagogical effectiveness differences, observable student engagement pattern variations, learning outcome quality assessments, and practical AR technology integration challenges encountered during actual instructional implementation. This dual stakeholder group design proved essential because training effectiveness is fundamentally determined by the complex interaction between learner competency development trajectories and instructor capacity to effectively leverage available technology for pedagogical optimization, curricular alignment, and individualized learning support [6].

The primary quantitative survey instrument comprised 36 carefully designed structured items systematically organized across five theoretically grounded competency and experience assessment domains: First, spatial awareness development, measuring self-assessed improvement in developing and maintaining accurate mental models of vessel position, traffic situation comprehension, and hazard proximity awareness. Second, collision avoidance decision-making, assessing demonstrated competency in identifying collision risk situations, evaluating maneuver options, and executing appropriate collision avoidance actions conforming to international regulations. Third, navigational skill acquisition, capturing overall proficiency development in essential technical skills including chart work accuracy, position fixing precision, course planning effectiveness, and situational assessment quality. Fourth, training engagement and learning satisfaction, measuring sustained attention during training sessions, intrinsic motivation to practice and improve, and overall learning experience quality perceptions. Fifth, AR-specific usability and cognitive load, evaluating AR interface ease of use, technological system reliability, information presentation clarity, and cognitive effort required for effective technology utilization during training tasks.

Survey items employed carefully calibrated five-point Likert scales enabling precise measurement of agreement levels, competency self-assessments, and experience quality ratings. The complete survey instrument demonstrated strong internal consistency reliability with Cronbach's alpha coefficient of 0.90, substantially exceeding the 0.70 threshold typically considered acceptable for research instruments and approaching the 0.95 threshold considered excellent, indicating that survey items consistently and reliably measured intended constructs [5].

Four comprehensive FGD sessions were systematically conducted following survey data collection—two sessions with nautical cadets (n = 12 participants each, total n = 24) and two sessions with simulator instructors (n = 9 participants each, total n = 18)—with session durations ranging from 90 to 110 minutes enabling detailed exploration of complex topics while maintaining participant engagement and discussion quality. FGD sessions employed carefully structured discussion guides explicitly aligned with the five survey assessment domains to enable systematic integration of quantitative survey patterns with qualitative explanatory insights, ensuring that qualitative data directly addressed questions raised by quantitative findings rather than exploring tangential topics [6].

Survey data were analyzed using SPSS statistical software version 26 employing paired-samples t-tests comparing AR-enhanced training condition scores with traditional training condition scores across all measured competency domains and experience dimensions, with statistical significance threshold set at $p < 0.05$ and effect sizes calculated using Cohen's d to assess practical significance beyond mere statistical significance [5]. FGD audio recordings were professionally transcribed verbatim, and transcripts were systematically analyzed using established thematic analysis procedures [7] involving initial independent coding by two researchers, collaborative identification of recurring themes and patterns, iterative theme refinement through discussion, and final validation ensuring themes accurately represented participant perspectives and captured key insights regarding AR training experiences, perceived learning benefits, technological challenges, and pedagogical recommendations.

3. RESULTS AND DISCUSSION

3.1 Results

The integrated analysis of quantitative survey data and qualitative FGD insights produced compelling and convergent evidence that AR-enhanced ship handling simulation training significantly improves nautical competency development across multiple critical skill domains while simultaneously increasing student engagement levels, training satisfaction, and perceived learning effectiveness relative to traditional bridge simulation training approaches that have dominated maritime education for decades [3].

Table 1 presents comprehensive mean competency scores comparing AR-enhanced training with traditional simulation training across all measured domains.

Table 1. AR-Enhanced vs. Traditional Simulation Training: Mean Competency Scores ($N = 120$ cadets)

Competency Domain	AR Training	Traditional Training	Improvement (%)	Significance
Spatial Awareness Development	4.31	3.28	+31.4%	$p < .001$
Collision Avoidance Decision-Making	4.18	3.31	+26.3%	$p < .001$
Navigational Skill Acquisition	4.24	3.37	+25.8%	$p < .001$
Training Engagement	4.47	3.52	+27.0%	$p < .001$
Overall Satisfaction	4.38	3.44	+27.3%	$p < .001$
Mean Competency Index	4.32	3.38	+27.8%	$p < .001$

Note: Scale: 1.00–1.79 = Very Low; 1.80–2.59 = Low; 2.60–3.39 = Moderate; 3.40–4.19 = Good; 4.20–5.00 = Excellent. All differences significant at $p < .001$ (paired-samples t-test)

The overall mean competency improvement of 27.8 percent achieved through AR-enhanced training represents not merely a statistically significant difference but an educationally and practically significant effect size (Cohen's $d = 1.24$, considered large by conventional standards), with spatial awareness development showing the largest absolute gain at 31.4 percent improvement—directly confirming theoretical predictions that AR's distinctive visual overlay capabilities would particularly enhance the fundamental spatial reasoning competencies that underpin safe navigation practice [4]. Paired-samples t-tests confirmed highly significant differences ($p < .001$) for all measured competency domain comparisons with consistently large effect sizes across all domains, indicating that AR training advantages are robust, substantial, and consistent rather than limited to specific narrow skill areas.

Table 2 presents scenario-specific performance assessment data based on instructor evaluations of cadet performance across diverse ship handling scenarios representing varying complexity levels and risk profiles.

Table 2. Instructor-Assessed Performance: Scenario-Specific Competency ($N = 120$ cadets, 18 instructors)

Ship Handling Scenario	AR Mean Score	Traditional Mean Score	Improvement	Scenario Type
Harbor Approach in Traffic	4.42	3.41	+29.6%	Complex
Collision Avoidance Maneuver	4.28	3.37	+27.0%	Critical
Restricted Visibility Navigation	4.51	3.29	+37.1%	High-Risk
Anchoring Procedure Execution	4.14	3.48	+19.0%	Technical
Emergency Steering Failure	4.39	3.33	+31.8%	Emergency
Weighted Mean	4.35	3.38	+28.7%	All Scenarios

The detailed scenario-specific analysis reveals a critically important pattern: AR-enhanced training generates proportionally larger performance improvements precisely in the most complex, cognitively demanding, and operationally high-risk training scenarios where traditional simulation approaches struggle most to support effective learner performance [3]. Restricted visibility navigation, which represents one of the most challenging and dangerous operational conditions requiring integration of radar, visual lookout, sound signals, and safe speed judgment, showed the largest improvement at 37.1 percent, while emergency steering failure scenarios requiring rapid assessment and implementation of backup steering procedures showed 31.8 percent improvement. This pattern strongly suggests that AR's decision-support overlays, real-time feedback mechanisms, and integrated information presentation provide greatest pedagogical value precisely where cognitive task demands are highest and where traditional simulation's fragmented information presentation across multiple separate displays creates the greatest cognitive load and learning barriers.

Qualitative FGD data systematically analyzed using rigorous thematic analysis procedures illuminated the specific pedagogical mechanisms and cognitive processes underlying the substantial quantitative competency improvements documented in survey and instructor assessment data [7]. The dominant and most consistently expressed theme emerging from cadet FGD sessions was "immediate spatial comprehension"—the transformative experience of having AR visual overlays make inherently abstract spatial relationships tangible, concrete, and immediately graspable in ways that traditional navigation chart interpretation, radar display reading, and mental calculation fundamentally cannot achieve regardless of training duration or instructor expertise.

Cadets provided detailed descriptions of how seeing their vessel's projected future course line overlaid directly onto the harbor environment in precise spatial alignment with physical features instantly clarifies whether their planned navigational maneuver will safely clear other traffic, avoid shallow water, and maintain required distances from hazards, whereas determining identical information from traditional radar displays and paper navigation charts requires complex mental spatial transformations, mathematical calculations, and abstract visualization processes that introduce significant time delays, increase error potential, and create cognitive load that impedes rather than supports decision-making under operational pressure [4].

Simulator instructors participating in FGD sessions identified "scaffolded complexity reduction" as AR technology's primary and most valuable pedagogical mechanism—the capability of AR visual overlays to provide targeted decision-support scaffolding that strategically reduces extraneous cognitive load during complex scenarios, thereby enabling students to focus limited cognitive resources on higher-order decision-making, strategic planning, and professional judgment development rather than becoming overwhelmed by the massive information interpretation and integration demands that characterize complex navigation situations [1]. One experienced instructor with over fifteen years of bridge simulation teaching articulated this insight compellingly: "In traditional simulation training, students confronting restricted visibility scenarios often become essentially paralyzed trying to simultaneously process radar returns, interpret ECDIS chart displays, maintain visual lookout, monitor AIS target information, and integrate all these separate information sources into coherent situational awareness. The cognitive overload simply shuts down effective decision-making. AR overlays fundamentally transform this challenge by integrating these multiple disparate information streams directly into students' unified visual field, keeping critical information cognitively available for immediate decision-making utilization rather than forcing students to freeze in information overload or make decisions based on incomplete situational comprehension."

3.2 Discussion

The comprehensive empirical findings provide robust and convergent evidence from multiple data sources that AR-enhanced ship handling simulation training significantly and substantially improves nautical competency development, with overall mean gains of 27.8 percent across all measured domains and scenario-specific improvements reaching 37.1 percent in the most complex and operationally critical training contexts that most closely approximate the cognitive demands and performance requirements of actual shipboard watchkeeping [3]. These substantial improvements represent not merely incremental enhancement of existing training approaches but potentially transformative advancement in maritime education's capacity to develop the sophisticated spatial reasoning, rapid situational assessment, and sound professional judgment that characterize expert bridge officer performance.

These quantitative findings align with and significantly extend the limited existing research literature examining AR applications in maritime-related training contexts, corroborating Zhu et al.'s [4] systematic documentation of 20 to 30 percent performance improvements in AR-enhanced marine engineering maintenance training applications and Burova et al.'s [3] experimental demonstration of superior spatial learning outcomes achieved through AR-enhanced navigation skill training compared with traditional instructional methods. However, the present study substantially advances these foundational contributions by

providing the first systematic, rigorous competency assessment specifically focused on complex ship handling decision-making under realistic operational pressure—the most critical, pedagogically challenging, and professionally consequential competency domain in bridge officer professional development that has remained largely unexplored in prior AR maritime training research despite its central importance.

The particularly large performance improvements documented in restricted visibility navigation scenarios (37.1 percent improvement) and emergency response situations (31.8 percent improvement) carry profound pedagogical implications extending beyond simple training effectiveness metrics [1]. These differential results across scenario types suggest that AR technology's fundamental value proposition for maritime training is not merely producing modest incremental improvement distributed uniformly across all training activities, but rather achieving transformative enhancement precisely in those specific high-complexity, high-cognitive-load scenarios where traditional simulation approaches are demonstrably weakest and where the gap between simulation training and operational reality is largest and most consequential for safety.

Hontvedt's [1] influential ethnographic analysis argued persuasively that traditional bridge simulators fundamentally struggle to authentically replicate the situated, embodied decision-making processes that characterize actual shipboard watchkeeping because the profound perceptual disconnection between computer-generated simulator screen displays and trainees' physical environment systematically disrupts the essential sensorimotor integration, embodied spatial awareness, and unified perceptual-cognitive processing that expert navigation performance requires. AR technology directly addresses this fundamental limitation by preserving rather than replacing physical embodiment and real-world sensorimotor interaction while strategically augmenting physical perception with precisely targeted digital information overlays, creating uniquely hybrid learning experiences that more authentically approximate the integrated perceptual-cognitive-motor experience that characterizes actual shipboard navigation practice than either purely physical training or purely virtual simulation can achieve independently [2].

The qualitative FGD-identified theme of "immediate spatial comprehension" illuminates a specific and theoretically important cognitive mechanism through which AR enhances learning effectiveness beyond simple information provision [8]. Spatial reasoning research has extensively documented that externalizing complex mental spatial transformations through appropriate visual aids and representations substantially reduces working memory cognitive load, decreases error rates in spatial judgment tasks, and accelerates skill acquisition by making normally invisible cognitive operations visible and thereby enabling more effective practice with immediate corrective feedback. AR navigational overlays externalize the sophisticated spatial transformations that navigators must typically perform entirely mentally and invisibly—visualizing projected future course lines, estimating closest points of approach with other traffic, assessing collision risk based on relative motion, predicting vessel response to control inputs—making these normally invisible cognitive operations explicitly visible in real-time and thereby simultaneously reducing immediate cognitive load while systematically building durable spatial reasoning competency through repeated practice cycles with immediate visual feedback regarding accuracy [4].

The "scaffolded complexity reduction" mechanism identified by experienced simulator instructors points toward AR's particular value for managing the well-documented challenge of cognitive overload in complex training scenarios [3]. Cognitive load theory demonstrates that learning effectiveness depends critically on managing the total cognitive demands imposed on learners' limited working memory capacity, with excessive cognitive load impeding rather than supporting learning by overwhelming processing capacity and preventing effective schema construction. Traditional bridge simulation, particularly in complex scenarios requiring integration of multiple information sources, often inadvertently imposes high extraneous cognitive load through fragmented information presentation across separate radar displays, chart plotters, visual windows, and instrument panels that must be mentally integrated through effortful cognitive processing. AR overlays reduce this extraneous load by presenting integrated information within unified visual fields, freeing cognitive resources for the germane cognitive processing that actually builds professional competency rather than merely managing information access logistics [1].

4. CONCLUSION

This rigorous mixed-methods empirical study provides compelling evidence that AR-enhanced ship handling simulation training significantly and substantially improves spatial awareness development by 31.4 percent, collision avoidance decision-making competency by 26.3 percent, and overall nautical competency by 27.8 percent relative to traditional bridge simulation training approaches at STIP Jakarta, with proportionally greatest improvements concentrated in the most complex, cognitively demanding restricted visibility and emergency response scenarios where cognitive demands are highest and where traditional simulation struggles most to support effective learning. Real-time position overlay visualizations and integrated collision warning

systems emerge from both quantitative performance data and qualitative instructor assessment as the most pedagogically valuable and practically effective AR features, providing targeted decision-support scaffolding that strategically reduces extraneous cognitive load while simultaneously building durable spatial reasoning competency through repeated practice cycles with immediate, precise visual feedback integrated directly into trainees' operational field of view.

The AR Maritime Simulation Integration Framework proposed by this study based on systematic analysis of empirical findings incorporates four essential strategic components for effective implementation: First, comprehensive position overlay systems displaying real-time vessel position, projected course lines, turning radius predictions, and safety zone visualizations integrated with physical training environments. Second, intelligent collision warning applications providing target vessel tracking, closest point of approach calculations, collision risk assessments, and safe maneuver guidance overlaid onto operational views. Third, realistic environmental condition simulation capabilities enabling fog, rain, darkness, and reduced visibility training scenarios deliverable flexibly within standard daytime training schedules without requiring expensive physical condition replication. Fourth, systematic instructor professional development providing AR-mediated pedagogy training, technology integration strategies, and debriefing techniques optimized for AR-enhanced learning experiences.

This evidence-grounded framework provides STIP Jakarta and other maritime education institutions with actionable, empirically validated guidance for expanding AR technology adoption strategically across bridge simulator training programs while ensuring that substantial technological investments translate reliably into measurable nautical competency improvements that enhance graduate professional readiness for the complex demands of modern ship operations. The framework emphasizes that effective AR implementation requires coordinated attention to technology selection, pedagogical design, instructor preparation, and systematic outcome assessment rather than simple technology deployment, recognizing that educational technology effectiveness depends fundamentally on thoughtful integration with sound pedagogical principles and institutional support structures.

Future research should investigate AR training effectiveness for specialized vessel types including tankers, bulk carriers, and passenger vessels with distinct handling characteristics, examine long-term competency retention and transfer to actual shipboard performance, and explore optimal combinations of AR and traditional simulation for comprehensive competency development across the full spectrum of bridge officer professional preparation requirements.

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