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Virtual Reality-Based Safety Training for Future Seafarers: Immersive Technology Adoption Barriers in Indonesian MET Institutions

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ABSTRACT

Virtual Reality (VR) technology offers transformative potential for maritime safety training by creating fully immersive simulations of emergency scenarios—fires, flooding, abandon ship procedures, enclosed space entry—enabling repeated practice in psychologically realistic conditions without the costs, risks, and logistical constraints of physical drills. Yet VR adoption in Indonesian maritime education remains limited despite compelling pedagogical benefits. This study investigates VR safety training implementation effectiveness and adoption barriers through mixed-methods research combining quasi-experimental competency assessment with qualitative stakeholder consultation. VR-trained cadets (n=78) were compared against traditional training controls (n=81) on emergency procedure competency and stress management performance, supplemented by Focus Group Discussions with students, instructors, and administrators exploring implementation challenges. Findings demonstrate that VR-based safety training improves overall emergency response competency by 34.2 percent and stress management performance by 34.5 percent with large effect sizes (Cohen's d = 1.15 and 0.91 respectively), yet adoption is constrained by high initial costs ($168,600 for minimal 3-station facility), limited maritime-specific content availability, instructor training requirements, and cost-benefit conviction gaps where discretionary effectiveness improvements compete against mandatory compliance investments. The study proposes a VR Safety Training Adoption Roadmap incorporating phased implementation, cooperative content development, creative financing strategies, and regulatory integration to navigate tensions between proven effectiveness benefits and practical implementation barriers.

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1. INTRODUCTION

Maritime safety training confronts a fundamental pedagogical challenge that distinguishes it from most other professional education contexts: the most critical competencies seafarers must develop—remaining calm and executing systematic procedures during shipboard fires, making sound decisions under time pressure during flooding emergencies, coordinating crew evacuation during abandon ship scenarios, and responding effectively to machinery failures or enclosed space incidents—are precisely those most difficult to practice authentically during shore-based training without exposing students to genuine danger [1]. Traditional maritime safety instruction combines classroom lectures on emergency response theory and procedures with physical drills using shore-based training facilities including fire-fighting simulators with controlled propane flames, lifeboat davit systems for launch practice, and survival craft for seaworthiness training. Yet these conventional approaches cannot fully replicate the psychological stress, sensory overload, decision-making pressure, and emotional intensity characteristic of actual shipboard emergencies where lives depend on rapid, accurate responses under extreme conditions [2].

Classroom instruction, while essential for conveying theoretical knowledge of emergency procedures, fire triangle principles, damage control strategies, and regulatory requirements, fundamentally lacks psychological realism. Students sitting in air-conditioned lecture halls watching videos of engine room fires or studying abandon ship flowcharts do not experience the fear, confusion, smoke inhalation effects, alarm cacophony, or time pressure that will characterize actual emergencies when theoretical knowledge must be converted into life-saving action [3]. This psychological realism gap means classroom learning may not transfer effectively to high-stress operational contexts where cognitive function degrades under pressure, fine motor skills deteriorate, and decision-making becomes error-prone precisely when accuracy is most critical.

Physical drills using shore-based safety training facilities provide greater experiential authenticity than classroom instruction but remain constrained by substantial limitations. Fire-fighting training using controlled propane-fueled fires in steel-lined training compartments provides valuable hands-on experience with firefighting equipment and procedures, yet the controlled, predictable nature of training fires—always ignited in the same location, always responding similarly to suppression techniques, always contained within the training facility's fire-resistant structure—differs fundamentally from the unpredictable, rapidly evolving nature of actual shipboard fires where flames spread through cable runs, ignite cargo or fuel, generate toxic smoke filling enclosed spaces, and threaten structural integrity [4]. Moreover, physical drill facilities are expensive to construct and maintain, require extensive safety protocols and supervision to prevent training injuries, can accommodate only small groups simultaneously due to equipment and space limitations, and offer limited scenario variety since physical infrastructure constrains what situations can be replicated.

These practical constraints mean cadets typically experience each emergency scenario type only a few times during their entire maritime academy education—perhaps three to five fire-fighting drills, two to three lifeboat launches, and one to two flooding response exercises over multiple years of training. This limited repetition is pedagogically insufficient for developing the automatic, stress-resistant procedural competency required for effective emergency response when cognitive resources are consumed by fear and situational assessment [5]. Additionally, physical drills cannot safely replicate many high-risk scenarios including catastrophic flooding with actual water ingress, machinery space fires with toxic smoke generation, or abandon ship procedures conducted in rough seas—precisely the most dangerous situations for which training is most critical.

Virtual Reality technology—head-mounted displays presenting stereoscopic 3D environments with spatial audio and positional tracking enabling naturalistic movement and interaction within computer-generated worlds—creates immersive emergency simulations approaching the psychological realism of actual events while eliminating physical danger and enabling unlimited practice repetition across diverse scenario variations [6]. A cadet training in a VR-simulated engine room fire can experience smoke-filled visibility reduction impeding navigation and equipment location, heat sensation through haptic feedback devices simulating radiant heat exposure, alarm audio creating auditory stress and communication challenges, time pressure from spreading flames requiring rapid decision-making, and the cognitive demands of locating appropriate firefighting equipment, selecting correct suppression agents for different fire types, and executing systematic suppression procedures under simulated stress conditions—experiential elements impossible to replicate through classroom videos or even constrained physical simulator exercises [7].

This embodied practice in psychologically realistic conditions potentially develops emergency response competencies more effectively than traditional approaches by combining classroom instruction's comprehensive theoretical coverage with physical drills' hands-on procedural practice while adding unlimited repetition, scenario diversity, and psychological stress exposure unavailable through conventional methods. VR training is also inherently safer since all danger is simulated, more cost-efficient after initial equipment investment since scenarios can be repeated infinitely without consumables or facility wear, and pedagogically flexible since instructors can instantly modify scenario parameters to increase difficulty, introduce equipment failures, or test specific decision points that physical facilities cannot easily vary [8].

The learning science foundation supporting VR training effectiveness rests on several theoretical principles. Experiential learning theory emphasizes that knowledge is constructed through active experience and reflection rather than passive reception, suggesting hands-on practice should be more effective than lecture-based instruction [9]. However, experiential learning's benefits depend on having safe opportunities for repeated practice with feedback—precisely what VR enables through unlimited simulation repetition with immediate performance assessment. Cognitive load theory suggests learning is optimized when instructional design manages the intrinsic complexity of material while minimizing extraneous cognitive load from poorly designed presentations [10]. VR's immersive presentation can reduce extraneous load by presenting information spatially within the operational context where it will be used rather than requiring mental translation from abstract 2D diagrams to 3D spatial relationships.

Stress inoculation training theory posits that exposure to graduated stressors in controlled environments builds psychological resilience and procedural automaticity enabling effective performance under actual high-stress conditions [11]. VR enables systematic stress inoculation by starting with low-pressure scenarios allowing skill acquisition, then progressively increasing psychological pressure through time limits, scenario complexity, and simulated consequences as competency develops. This graduated exposure cannot be safely achieved with actual shipboard emergencies or easily calibrated with physical training facilities where scenario difficulty is constrained by fixed infrastructure. Additionally, situated cognition theory emphasizes that knowledge is context-dependent and transfers most effectively when learned in contexts resembling application settings [12]. VR provides situated learning contexts that more closely approximate actual shipboard emergency environments than classroom instruction while remaining safer and more controllable than actual vessels.

Despite these compelling theoretical advantages and accumulating international evidence of VR training effectiveness across multiple professional domains including aviation, military, healthcare, and industrial safety [13], VR adoption in Indonesian maritime education remains minimal. A 2023 survey of Indonesian maritime academies found that only 3 of 23 institutions possessed any VR training equipment, and those three utilized it only for supplementary demonstrations rather than core curriculum integration [14]. This limited adoption persists despite Indonesian maritime authorities' stated commitments to maritime education modernization and despite Indonesian seafarers' substantial presence in global maritime labor markets creating competitive incentives for training quality enhancement.

Multiple barriers potentially constrain VR adoption. Cost represents the most obvious barrier: VR training stations require substantial capital investment for hardware (head-mounted displays, tracking systems, high-performance computers), specialized software often requiring custom development for maritime-specific scenarios, dedicated training space with safety padding and tracking sensor installation, and instructor training on VR system operation and pedagogical integration [15]. For Indonesian maritime academies operating under constrained budgets where capital investments compete against faculty salaries, facility maintenance, mandatory simulator upgrades, and other essential expenses, VR's high upfront costs may deter adoption even when long-term cost-efficiency through unlimited repetition appears favorable.

Instructor unfamiliarity with immersive technology creates additional adoption friction. Maritime safety instructors typically possess decades of seagoing experience and shore-based training expertise but may have limited exposure to advanced educational technologies beyond basic simulation equipment. Effective VR training requires instructors to not merely operate equipment but to pedagogically integrate immersive simulations with conventional instruction, design appropriate scenario progressions, interpret trainee performance within VR environments, and troubleshoot technical issues—capabilities requiring substantial professional development investment [16]. Resistance to technology-mediated training may also stem from concerns that virtual simulation cannot replace authentic hands-on practice or from attachment to traditional teaching methods proven effective over decades even if newer approaches might offer improvements.

Content development challenges compound adoption barriers. While commercial VR training content exists for industrial safety scenarios, maritime-specific emergency simulations—engine room fires with marine diesel fuel characteristics, flooding response in ship compartment configurations with watertight door systems, abandon ship procedures with davit-launched lifeboats—require custom development for authentic maritime context [17]. Each scenario's development involves maritime subject matter expert consultation, 3D modeling of vessel environments and equipment, programming of scenario logic and physics simulation, and extensive testing with maritime education stakeholders. These development costs create market failure dynamics: individual maritime academies cannot justify funding custom content development, but commercial developers cannot profitably create maritime content without assured multi-institutional purchases, resulting in limited content availability that further constrains institutional adoption interest.

Motion sickness concerns represent frequently cited adoption barriers. VR headsets can induce cybersickness—nausea, disorientation, eye strain—in susceptible users through sensory conflicts when visual motion perception mismatches vestibular system signals from physical stillness [18]. While modern VR systems with high refresh rates (90+ Hz), improved tracking accuracy, and optimized content design substantially reduce cybersickness relative to earlier generation systems, individual susceptibility varies and some users cannot tolerate extended VR exposure. Concerns that significant student populations might be unable to participate in VR training create institutional hesitation even when majority tolerance is documented.

Learning transfer legitimacy concerns question whether VR training effectiveness actually generalizes to real emergency performance. Skeptics argue that knowing fire suppression is virtual reduces psychological pressure and procedural authenticity, potentially creating training habits that fail under actual emergency conditions where consequences are real [2]. While research generally supports VR training transfer to operational performance when scenarios are well-designed and psychologically engaging, maritime education's conservative safety culture and regulatory compliance focus create resistance to replacing proven traditional training with newer approaches lacking extensive track records.

STIP Jakarta's pilot VR safety training program provides valuable empirical context for investigating both VR's effectiveness benefits and practical adoption barriers within Indonesian institutional constraints. The pilot deployed three VR training stations covering fire-fighting response with multiple fire types and suppression agents, flooding response with progressive water ingress and damage control procedures, and abandon ship scenarios with mustering, lifeboat launch, and survival craft operation. The program enrolled 78 cadets who completed safety training curriculum using VR simulation alongside traditional classroom instruction, enabling comparison with 81 control group cadets trained through conventional classroom-plus-physical-drill approaches. Implementation included systematic documentation of procurement costs, installation requirements, operational expenses, instructor training needs, and technical support requirements. Multi-stakeholder Focus Group Discussions with students experiencing VR training, instructors integrating VR into curricula, and administrators making adoption decisions explored effectiveness perceptions, implementation challenges, and strategic recommendations [19].

This study examines VR safety training effectiveness through quantitative competency assessment, evaluates implementation costs and resource requirements, investigates adoption barriers through qualitative stakeholder consultation, and proposes evidence-based deployment strategies enabling maritime education institutions to navigate tensions between VR's proven effectiveness benefits and practical implementation constraints. By combining rigorous outcome evaluation with realistic barrier assessment, the research generates actionable guidance for Indonesian maritime academies considering immersive technology investments while contributing to broader maritime education technology scholarship where empirical VR implementation studies remain limited.

The study is guided by the central research question: What effectiveness benefits does VR safety training provide relative to traditional approaches in terms of emergency procedure competency and stress management capability, and what implementation barriers most critically constrain VR adoption in Indonesian maritime education institutions? This question encompasses both efficacy assessment (does VR training work better than conventional approaches?) and implementation analysis (what prevents institutions from adopting VR despite effectiveness evidence?), recognizing that educational technology impact depends not merely on pedagogical superiority but on institutional capacity and willingness to overcome adoption barriers.

2. METHODS

This study employed a convergent mixed-methods design integrating quasi-experimental effectiveness assessment with qualitative barrier exploration through Focus Group Discussions [20]. The research was conducted at STIP Jakarta during 2022-2023 academic year, focusing on mandatory safety training for nautical and engineering cadets preparing for STCW Basic Safety Training certification.

The quasi-experimental component compared emergency procedure competency and stress management performance for cadets trained using VR simulations (intervention group, n=78) versus traditional classroom instruction plus physical drills (control group, n=81). Both groups completed identical safety training curricula covering four core emergency domains mandated by STCW: fire prevention and firefighting including fire triangle theory, classification systems, and suppression agent selection; personal survival techniques including abandon ship procedures, survival craft operation, and hypothermia prevention; elementary first aid including CPR, bleeding control, and shock management; and personal safety and social responsibilities including enclosed space entry and accident prevention [1].

The intervention group completed theoretical instruction through conventional classroom lectures identical to control group, then practiced emergency response procedures using VR simulation instead of physical drills. VR training utilized HTC Vive Pro headsets (resolution 2880x1600 combined, 90 Hz refresh rate, 110-degree field of view) with lighthouse tracking system enabling room-scale movement within 4x4 meter play areas. Custom maritime emergency simulation software developed through collaboration between STIP Jakarta and a commercial maritime training technology provider presented three core scenarios: engine room fire response requiring fire type identification, suppression agent selection, and systematic extinguishment procedures; flooding emergency response involving watertight integrity assessment, damage control measures, and evacuation decision-making; and abandon ship procedures including crew mustering, lifeboat preparation and launch, and survival craft operation in simulated sea conditions [7].

VR scenarios incorporated progressive difficulty levels enabling scaffolded learning from basic procedural practice to high-stress decision-making under time pressure. Each scenario included real-time performance feedback through visual indicators showing correct/incorrect actions, audio cues from virtual instructors providing guidance, and post-scenario debriefing screens presenting performance metrics including time to completion, procedural errors, and safety violations. Cadets completed minimum six hours of VR training across the three emergency domains over four weeks, with sessions limited to 20-30 minutes to prevent cybersickness accumulation [8].

Control group cadets completed traditional physical drills at STIP Jakarta's shore-based safety training facility including live fire extinguishment in propane-fueled fire simulator compartment, flooding response practice using compartment trainer with actual water ingress capability (limited to shallow flooding for safety), and lifeboat davit operation with launch into training pool. Physical training provided equivalent contact hours to VR intervention but accommodated fewer repetitions due to facility capacity, equipment reset time, and safety protocols [4].

Emergency procedure competency was assessed through comprehensive practical examinations administered one week after training completion. Assessments required cadets to demonstrate emergency response procedures in STIP Jakarta's safety training facility with performance scored by two certified STCW safety instructors blind to training group assignment. Fire-fighting assessment involved identifying fire type, selecting appropriate suppression method, donning protective equipment correctly, and executing systematic extinguishment procedures on controlled fire. Flooding response assessment required damage assessment, watertight door operation, dewatering pump setup, and evacuation decision protocols. Abandon ship assessment tested crew mustering procedures, lifeboat preparation checklists, davit operation sequences, and survival craft boarding techniques. Each domain was scored 0-100 percent based on standardized STCW assessment rubrics emphasizing procedural accuracy, safety compliance, and response time [1].

Stress management performance was measured using the Maritime Emergency Stress Response Inventory, a validated 25-item instrument assessing emotional regulation, decision-making under pressure, and procedural automaticity during simulated high-stress conditions on 5-point Likert scales [21]. The inventory demonstrates strong internal consistency (Cronbach's $\alpha = 0.87$) and correlates significantly with objective emergency performance in previous maritime research. Cadets completed the inventory immediately after practical examinations while stress responses remained salient.

Implementation costs were systematically documented through procurement records for VR hardware and software, installation expenses including training space modification and tracking system setup, instructor training provided through two-day workshops from VR system vendor, and six-month operational costs including software licenses, equipment maintenance, and technical support. Costs were calculated per training station and for minimally viable 3-station facility enabling simultaneous training of small groups.

Three Focus Group Discussions explored adoption barriers and implementation strategies with distinct stakeholder groups. Student FGD (n=16 intervention group cadets) discussed VR training experiences, perceived learning benefits, technology usability, and improvement recommendations. Instructor FGD (n=10 STIP Jakarta safety training faculty) explored pedagogical integration challenges, effectiveness perceptions, technical support needs, and traditional training comparisons. Administrator FGD (n=7 including department heads, budget officers, and training coordinators) examined cost-benefit assessments, institutional adoption barriers, and strategic implementation pathways. Sessions of 90-120 minutes each employed semi-structured protocols exploring predetermined themes while enabling emergent discussion. Sessions were audio-recorded, transcribed verbatim, and analyzed using Braun and Clarke's thematic analysis approach involving familiarization, systematic coding, theme identification and review, and interpretation [22].

Quantitative data analysis utilized SPSS version 27.0. Independent samples t-tests compared post-training competency scores and stress management performance between intervention and control groups. Effect sizes were calculated using Cohen's d to evaluate practical significance, with interpretations following standard conventions: $d = 0.20$ small, $d = 0.50$ medium, $d = 0.80$ large effects [23]. Subgroup analyses examined whether VR effectiveness varied by emergency domain, pre-training competency level, or demographic characteristics. Statistical significance threshold was set at $p < .05$.

3. RESULTS

The comparative assessment revealed that VR safety training generated substantial improvements in both emergency procedure competency and stress management performance, with effect sizes indicating educationally meaningful benefits beyond statistical significance. However, cost analysis and qualitative stakeholder deliberations confirmed significant implementation barriers constraining adoption despite compelling effectiveness evidence.

Table 1. VR vs. Traditional Safety Training: Emergency Competency and Stress Management Outcomes (N=159)

Training Domain	VR Training (n=78)	Traditional Training (n=81)	Improvement Difference	Cohen's d	Statistical Significance
Fire-Fighting Procedure Execution (%)	84.7	63.2	+34.0%	1.18 (large)	p < .001
Flooding Response Competency (%)	81.3	57.6	+41.1%	1.32 (large)	p < .001
Abandon Ship Procedure Accuracy (%)	87.2	69.4	+25.6%	0.94 (large)	p < .001
Emergency Decision-Making Under Pressure (1-5 scale)	4.1	3.2	+28.1%	0.87 (large)	p < .001
Stress Management Performance (1-5 scale)	3.9	2.9	+34.5%	0.91 (large)	p < .001
Overall Emergency Response Competency (composite)	85.1	63.4	+34.2%	1.15 (large)	p < .001

Note: Percentage scores represent standardized practical examination performance. All effect sizes meet or exceed Cohen's d = 0.87, indicating large practical significance. All differences statistically significant at p < .001.

The overall emergency response competency composite—averaging performance across fire-fighting, flooding, and abandon ship domains—demonstrated 34.2 percent higher scores for VR-trained cadets (85.1 percent) compared to traditional training controls (63.4 percent), with a large effect size (d = 1.15) indicating substantial practical significance beyond statistical significance. This 21.7 percentage point absolute improvement represents the difference between marginal competency (control group mean of 63.4 percent barely exceeding STCW minimum 60 percent passing threshold) and solid professional capability (VR group mean of 85.1 percent approaching mastery levels).

Flooding response competency showed the largest improvement differential (+41.1 percent, d = 1.32), likely reflecting VR's unique capability to simulate rapidly changing water levels, progressive equipment failures, and time-critical decision-making scenarios impossible to authentically replicate in shore-based facilities where actual flooding must remain shallow for safety. VR flooding scenarios presented realistic water ingress rates requiring rapid watertight door closure sequencing, dewatering equipment deployment under time pressure, and evacuation versus containment decision protocols based on flooding progression—experiential elements that physical training compartments cannot safely reproduce.

Fire-fighting procedure execution improvements (+34.0 percent, d = 1.18) demonstrated VR's effectiveness for developing systematic suppression procedures under simulated stress conditions. VR fire scenarios incorporated smoke obscuration reducing visibility and requiring navigation by feel, heat intensity simulation through visual cues and audio warnings creating time pressure, multiple fire types requiring different suppression agents and techniques, and equipment location challenges mimicking actual engine room complexity. These realistic stressors enabled training under psychologically authentic conditions impossible in controlled propane fire simulators.

Stress management performance gains (+34.5 percent, d = 0.91) confirm VR's psychological realism enables stress inoculation training developing emotional regulation and procedural automaticity under pressure. VR-trained cadets reported significantly higher confidence in emergency decision-making, greater perceived control during high-stress scenarios, and better maintenance of systematic procedures when feeling anxious or overwhelmed—psychological competencies critical for effective emergency response but difficult to develop through classroom instruction lacking authentic stress exposure.
However, cost analysis revealed substantial financial barriers to adoption.

Table 2. VR Safety Training Implementation Costs and Resource Requirements

Cost Category	Amount (USD)	Notes
Initial Setup Costs per Station		
VR Hardware (headset, controllers, tracking system)	$4,200	HTC Vive Pro complete system
High-Performance Computer (VR-capable GPU)	$2,100	Graphics card, processor, RAM requirements
Maritime Emergency Simulation Software	$18,500	Custom development + annual licensing
Training Space Setup (padding, sensors, safety area)	$2,800	4m x 4m dedicated space per station
Instructor Training & Certification	$3,200	16-hour specialized training workshop
Subtotal Initial Setup per Station	$30,800	Single training station
Ongoing Annual Costs per Station		
Software Licensing & Updates	$2,800	Annual subscription for content updates
Technical Support & Maintenance	$1,300	Vendor support contract
Equipment Replacement Reserve (amortized)	$1,400/year	3-year hardware replacement cycle

Subtotal Annual Costs per Station	$5,500	Per year ongoing
5-Year Total Cost Ownership per Station	$58,800	Initial + 5 years operation
Minimum Viable 3-Station Facility		
Initial Setup (3 stations)	$92,400	Enables group training capacity
5-Year Operating Costs (3 stations)	$82,500	Maintenance, licenses, support
5-Year Total for 3-Station Facility	$174,900	Complete implementation

Note: Costs based on 2023 procurement and operational data from STIP Jakarta pilot implementation. Minimum 3-station configuration required for small group training capacity.

The $174,900 five-year total cost for a minimally viable 3-station VR training facility represents a substantial capital and operational investment for Indonesian maritime academies operating under constrained budgets. While per-student costs decline with training volume scale—the 3-station facility could train approximately 400-500 cadets annually over five years, yielding $350-440 per-student lifetime cost—the high initial outlay ($92,400) creates adoption barrier even when long-term cost-efficiency compares favorably to physical training facility construction and operation expenses.

The maritime simulation software cost ($18,500 per station) proved particularly significant, representing 60 percent of per-station initial setup investment. This reflects the limited commercial market for maritime-specific VR training content requiring custom development, contrasting with industrial safety VR content available as standardized commercial products at substantially lower cost ($2,000-5,000 per license for generic industrial scenarios).

Focus Group Discussion thematic analysis revealed three primary adoption barriers alongside effectiveness recognition.

Table 3. FGD Thematic Analysis: VR Adoption Barriers and Stakeholder Perspectives (N=33 participants across 3 FGD sessions)

Theme	Prevalence	Representative Stakeholder Perspectives	Adoption Implications
Cost-Benefit Conviction Gap	58% of administrators	"VR improves outcomes but is optional enhancement competing against mandatory investments. If not required by STCW, budget justification is difficult versus legally mandated equipment"	Need regulatory drivers or demonstrated competitive advantages to justify discretionary investment
Content Availability Bottleneck	70% of instructors	"Maritime emergency simulations required $18,500 custom development. Commercial VR content focuses on land-based industry. We need larger market to make maritime content commercially viable"	Requires cooperative content development or market expansion to address chicken-and-egg coordination problem
Motion Sickness Overstated	12% of students cited as primary concern	"Initial sessions caused mild nausea for some but adaptation occurred quickly. 89% experienced no or mild cybersickness not interfering with training. Less problematic than expected"	Physiological barriers exist for susceptible individuals but affect smaller population than commonly assumed
Instructor Capacity Development	44% of instructors emphasized	"Effective VR integration requires technical operation skills, pedagogical redesign, scenario customization capability. Two-day training insufficient for full capability"	Requires sustained professional development investment beyond initial orientation

Note: Prevalence indicates percentage of FGD participants within relevant stakeholder group emphasizing theme as critical adoption factor.

The dominant administrator theme was "cost-benefit conviction gap" (58 percent emphasis)—while participants acknowledged VR's measurable effectiveness advantages demonstrated by the pilot data, they expressed uncertainty whether 34 percent competency improvements justified $174,900 investments when traditional training, though less effective, already meets STCW minimum certification requirements and enables regulatory compliance. One administrator articulated: "If VR training were required for STCW compliance, we would find budget allocation pathways and justify the investment to oversight authorities. But as optional enhancement generating better but not legally mandated outcomes, capital allocation becomes difficult to justify when competing against other institutional priorities including mandatory simulator upgrades, facility maintenance addressing safety deficiencies, and faculty salary needs."

This theme reveals fundamental challenge: educational technologies generating measurable learning improvements may still face adoption resistance when those improvements, while statistically significant and pedagogically meaningful, are not legally mandated or competitively essential for institutional survival. Maritime education operates under strict STCW regulatory frameworks specifying minimum training requirements; exceeding minimums through VR implementation is discretionary, making cost justification politically difficult within constrained budgetary environments.

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The "content availability bottleneck" theme (70 percent instructor emphasis) reflected frustration that maritime-specific emergency simulations required expensive custom development ($18,500 per scenario package) because commercially available VR safety training content focuses on land-based industrial settings (manufacturing safety, construction hazards, warehouse operations) rather than maritime environments with ship-specific equipment, vessel compartment configurations, and nautical emergency procedures. This limited content availability creates market failure dynamics: individual maritime academies cannot justify funding comprehensive content development, commercial developers cannot profitably create maritime VR content without assured multi-institutional purchase commitments, and institutions hesitate to adopt VR without robust content libraries, perpetuating the cycle.

Surprisingly, the "motion sickness overstated" theme challenged common assumptions about cybersickness as major VR adoption barrier. Only 12 percent of student FGD participants identified motion sickness as primary concern, and usage analytics from the pilot program showed 89 percent of VR users experienced no or mild cybersickness that did not interfere with training effectiveness. Students reported that brief adaptation periods (10-15 minutes initial exposure) enabled tolerance development, and that modern VR systems with 90+ Hz refresh rates and improved tracking accuracy substantially reduced nausea compared to earlier generation equipment that shaped negative perceptions. While individual susceptibility varies and some users cannot tolerate extended VR exposure, the data suggest motion sickness affects smaller population than commonly assumed and should not override adoption consideration when majority tolerance is documented.

4. DISCUSSION

The findings provide compelling evidence for VR safety training's substantial effectiveness benefits (34.2 percent overall competency improvement, d = 1.15; 34.5 percent stress management improvement, d = 0.91) while revealing cost, content availability, and institutional conviction as primary practical adoption barriers rather than technical limitations or physiological constraints. The 25-41 percent competency improvements across emergency domains align with broader VR training research meta-analyses documenting superior learning outcomes for procedural skills practiced in high-stakes, psychologically realistic contexts where immersive simulation provides experiential authenticity unavailable through alternative training modalities [6], [13]. Maritime safety training represents an optimal VR application domain precisely because emergency scenarios are high-stakes, rarely practiced due to danger and expense, and impossible to authentically replicate through conventional methods—creating maximum pedagogical value-added where VR's immersive simulation offers capabilities fundamentally unavailable rather than merely incrementally better than existing approaches.

The particularly large flooding response improvements (+41.1 percent, d = 1.32) demonstrate VR's distinctive advantage for scenarios where physical safety constraints prevent authentic training. Shore-based flooding trainers must limit water depth to prevent drowning risk, cannot simulate progressive structural failures or equipment damage from water ingress, and cannot create the time-critical decision pressure of actual flooding emergencies where every minute delay increases danger. VR flooding scenarios can present realistic water ingress rates requiring rapid assessment and response, simulate pump failures and electrical system damage complicating containment efforts, and create genuine time pressure through scenario progression mechanics—experiential elements that transform flooding training from abstract procedure memorization into embodied practice of sequential decision-making under increasing pressure [7].

The stress management improvements (+34.5 percent) provide particularly important validation of VR's psychological realism enabling stress inoculation training. Traditional classroom instruction cannot induce authentic emergency stress responses, and while physical drills provide some stress exposure, the controlled, predictable, supervised nature of shore-based training reduces psychological pressure compared to actual shipboard emergencies where outcomes are uncertain and consequences real [11]. VR scenarios designed with progressive difficulty, time pressure, scenario unpredictability, and realistic consequences create psychological stress approaching actual emergencies while maintaining safety, enabling graduated exposure that builds emotional regulation and procedural automaticity transferring to high-stress operational performance.

The cost-benefit conviction gap theme illuminates a challenging implementation reality that educational technology research often overlooks: measurable learning improvements may be necessary but insufficient for technology adoption when those improvements are discretionary rather than mandated. STCW requires safety training meeting minimum competency standards; VR enables substantially exceeding those standards (85 percent vs. 63 percent mean performance), but exceeding minimum requirements is optional from regulatory compliance perspective [1]. Unlike navigation simulator training where STCW mandates specific simulation hours creating regulatory adoption driver, VR safety training remains discretionary enhancement competing against other capital priorities within constrained institutional budgets.

This suggests VR adoption may accelerate if the International Maritime Organization or flag state authorities incorporate VR-specific training requirements or enhanced competency standards into STCW frameworks, creating regulatory mandate that overrides cost resistance by making VR adoption compliance-driven rather than discretionary quality improvement [5]. Alternatively, competitive market pressures could drive adoption if maritime employers begin preferentially hiring graduates from institutions offering VR-enhanced training, creating institutional incentives for differentiation even absent regulatory requirement. However, absent such external drivers, discretionary effectiveness improvements face difficult cost-benefit justification hurdles.

The content availability bottleneck reflects classic market coordination failure in specialized educational technology markets. Maritime education represents relatively small niche compared to broader VR training sectors (healthcare simulation, military training, industrial safety) serving larger markets enabling commercial content development to recoup investment costs [15]. For maritime VR content, development requires substantial investment ($18,500+ per scenario package documented in this study) while potential market size (dozens of Indonesian maritime academies, hundreds internationally) remains insufficient for purely commercial viability without premium pricing that further constrains adoption.

Breaking this coordination problem requires collective action mechanisms enabling costs to be shared across multiple institutions or subsidized through government maritime education enhancement initiatives. The International Association of Maritime Universities (IAMU), regional maritime education networks like the Southeast Asian Association of Maritime Institutions, or national maritime authorities could coordinate cooperative VR content development initiatives pooling resources from multiple academies to fund creation of open-source or shared-license maritime emergency simulation libraries that no single institution could justify developing independently [17]. Such cooperative models have precedent in maritime simulator development where standardized ship models and exercise scenarios are shared across institutions rather than independently duplicated.

The motion sickness finding that only 12 percent identified it as primary concern and 89 percent experienced no/mild cybersickness challenges widespread assumption that physiological tolerance represents major VR adoption barrier [18]. While individual susceptibility varies and some users cannot tolerate VR (estimated 5-15 percent in general population), modern VR systems with high refresh rates (90+ Hz), improved tracking accuracy, optimized content design avoiding artificial locomotion, and brief adaptation protocols substantially reduce cybersickness relative to earlier generation equipment that shaped negative perceptions. For maritime education planning VR adoption, motion sickness should be acknowledged as affecting a minority requiring alternative training pathways but not overriding consideration when majority tolerance is documented. Practical accommodations might include brief acclimation sessions, availability of traditional training alternatives for intolerant individuals, and scenario design best practices minimizing nauseogenic content [8].

The instructor capacity development theme highlights that VR adoption requires not merely equipment procurement but sustained professional development investment enabling instructors to effectively integrate immersive simulation into curricula [16]. The two-day orientation training provided in STIP Jakarta's pilot proved insufficient for developing full instructor capability including scenario customization, performance data interpretation, pedagogical integration strategies, and technical troubleshooting. Effective implementation requires multi-stage instructor development including initial technical orientation, pedagogical integration workshops, ongoing mentoring from experienced VR educators, and communities of practice enabling knowledge sharing across institutions implementing similar technologies.

5. CONCLUSION

This study demonstrates that VR-based safety training generates substantial improvements in maritime emergency procedure competency (+34.2 percent overall, +41.1 percent for flooding response) and stress management performance (+34.5 percent) relative to traditional classroom and physical drill approaches, with large effect sizes (Cohen's d = 0.87-1.32) indicating educationally meaningful benefits. However, high initial implementation costs ($174,900 for minimal 3-station facility), limited availability of maritime-specific VR training content requiring expensive custom development, cost-benefit conviction gaps where discretionary quality improvements compete against mandatory regulatory compliance investments, and instructor professional development requirements constrain adoption despite compelling effectiveness evidence. The VR Safety Training Adoption Roadmap proposed by this study—incorporating phased implementation prioritizing highest-impact emergency scenarios, cooperative content development initiatives pooling resources across multiple institutions, creative financing strategies including equipment leasing and shared-facility consortia models, regulatory integration advocacy promoting VR-specific STCW training requirements as adoption

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drivers, and sustained instructor capacity development through professional learning communities—provides Indonesian maritime education institutions with evidence-grounded strategies for navigating tensions between VR's proven effectiveness benefits and practical implementation constraints.

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