

To Reality and Beyond: Employing XR to Facilitate Tacit Knowledge Flow

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Abstract

Tacit knowledge—experiential, embodied, and context-sensitive—is central in occupations requiring 1st person, spatial-temporal skills, but can be difficult or impossible to transfer, particularly in military domains. This study investigated whether Extended Reality (XR), delivered through low-cost commercial off-the-shelf (COTS) technology, could facilitate such knowledge flow for U.S. Navy (USN) bridge teams. A within-subjects design compared the Office of Naval Research Technical Solutions’ XR based Virtual Bridge and Nautical Trainer (VIBRaNT) to the Navy’s multi-million-dollar physical mockup system, the Navigation, Seamanship, and Shiphandling Trainer (NSST). Results showed that VIBRaNT XR compared favorably with NSST in perceptions of cognitive workload, system usability, and training preparation. Notably, XR-first training improved perceived mockup performance, suggesting XR has a positive impact on mockup training. These findings support XR as a viable, portable, and cost-effective complement to traditional training systems to build tacit knowledge in teams performing high-risk operations.

Keywords: Knowledge Flow, Embodied Cognition, Extended Reality, Synthetic Experience, Shiphandling

1. Introduction

The knowledge needed to safely maneuver warships at sea is inherently tacit, developed through embodied practice, and deeply social in nature. While traditional simulation systems like the NSST provide valuable structure and repetition, they are expensive to build and maintain, fixed in their location, and must remain generic to cover a wide variety of ship classes and bridge configurations. This shortfall presents an

opportunity for XR systems to fill the gaps, delivering immersive, high-fidelity experiences that complement traditional instruction while enhancing flows of knowledge across traditional learning boundaries.

This is critical to the USN as operational demands and system complexities continue to grow, placing greater cognitive demands on bridge watch teams. If skills once thought teachable only through a physical mockup could be developed in XR—with accuracy, nuance, and measurable effects—performance in high-risk settings of shiphandling, tactical maneuver, and combat operations could be greatly enhanced.

This urgency, underscored by fatal ship collisions in 2017, and a recent USN aircraft carrier collision in 2025, demands continuing vigilance. Physical mockups such as USN NSSTs have been a cornerstone of bridge training, but XR offers a similar environment without need of physical infrastructure. Because XR is mobile, always available, and affords advantages of an “information only” system, it holds promise to greatly enhance human performance.

In Figure 1, a screen capture of the VIBRaNT XR virtual environment (VE), shows the view from the bridge of a guided missile destroyer (DDG) entering San Diego Bay. Participant perception of the bridge, the channel, etc., mirrors, and in some ways, exceed the NSST mockup in replicating real world operations.

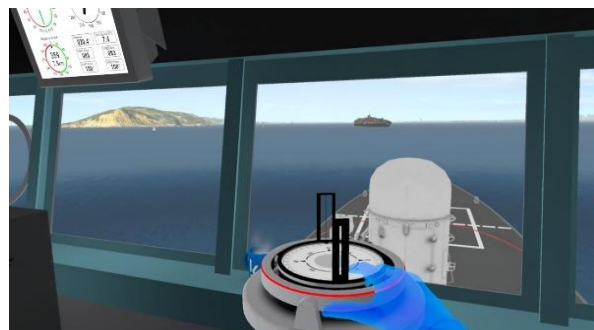


Figure 1. XR bridge virtual environment entering San Diego Bay. (Author, 2025)

Figure 2 shows a U.S. Navy crew training in XR in the USN's Mariner Skills Training Center Pacific (MSTCPAC) Classroom 215 in San Diego CA.



Figure 2. U.S. Navy bridge team training in VIBRaNT (Author, 2025)

This research, grounded in knowledge flow and embodied cognition theories, developed and conducted an experiment directly comparing XR-enabled training to the USN NSST mockup training system. Results showed XR offers the potential to facilitate and meaningfully support spatial-temporal learning and decision-making—core components of tacit shiphandling expertise needed by USN bridge teams—suggesting immersive, mobile XR systems offer a powerful complement to legacy mockups.

2. Background and related work

The following section reviews the theoretical framework and research hypotheses explored by this research to characterize the capacity of XR technology to flow tacit knowledge for operations conducted by USN bridge teams.

2.1. Knowledge flow

The concept of knowledge flow was central to this research. As theorized by Nissen, to be effective organizations must “flow knowledge” from those who possess it, to those who need it. Thus, when organizations discern and properly manage knowledge flows, knowledge utility can be optimized for competitive advantage (Nissen, 2002). Nissen conceptualizes knowledge flowing through a theoretical space defined in axes of life cycle, explicitness, and social reach (Nissen, 2006). An example of knowledge flow as conceived by Nissen is depicted in Figure 3.

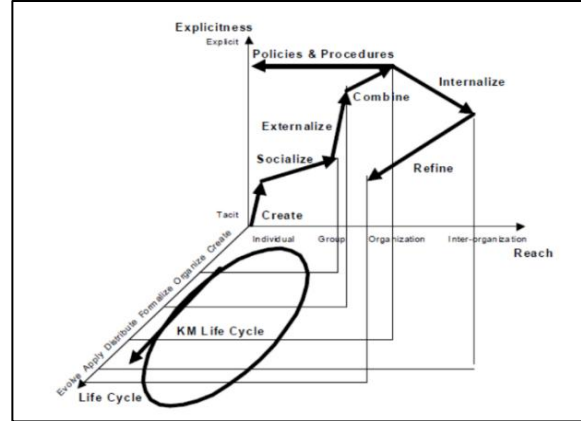


Figure 3. Multidimensional knowledge flow visualization model (Nissen, 2006)

Unlike management of information flow, where the conception of information “flowing” is relatively straightforward, managing knowledge flow demands a deeper appreciation of what is meant by the term “knowledge” (Nissen, 2014; Nonaka et al., 1996). Philosophically, knowledge is often categorized as episteme (propositional), techne (procedural), and empeiria (experiential) (Pavese, 2022; Sosa, 2020). Of these, techne and empeiria are usually categorized in Knowledge Management (KM) literature as being “tacit,” stemming, from Michael Polanyi’s famous quote “...one can know more than one can tell.” (Polanyi, 1967). Thus, expert tacit knowledge remains difficult to discern, acquire, and manage (Nissen & Bordetsky, 2011; Shigley, 2021).

Embodied cognition and extended mind theorists posit human learning and decision-making as processes distributed across an individual’s body, tools, and environment. From this perspective, knowledge is wholistic and ecological, not just in “one’s head” (Barrett, 2020; Chalmers, 2019; Clark, 2015, 2023; Varela et al., 2017).

Given these insights, managers must rely on more than written instruction, but also on embodied, context-sensitive experience with experts. Physical mockups have historically filled the gap of flowing tacit knowledge by providing experienced-based training in safe, high-fidelity environments (Bailenson, 2019). Only now is XR emerging as a readily available, cost-effective alternative.

Because XR HMDs can present information in an immersive way, participants “feel” an experience as if they are present in a “real life” situation. (Bailenson, 2019; Clark, 2023). In Figure 4, the author, projected as a “blue avatar”, stands at the center pelorus of an

XR generated DDG “bridge” much as he would if standing near a real pelorus (Figure 4).



Figure 4. “Blue Avatar” of the author on a bridge operating a pelorus. (Author, 2025)

By presenting information in the form of an immersive VE, an XR synthetic experience shows promise to flow tacit knowledge across teams (Alexias & Dimitropoulou, 2011; Alibali & Nathan, 2012; Bailenson, 2019; Wu et al., 2023). The structural coupling of users to an XR VE also aligns with connectionist neuroscience and embodied cognition (Gilson et al., 2010; Grant & Magee, 1998; Lakoff, 2012; Magee & Johnston, 1997) suggesting tacit learning can occur entirely in a digital setting (Mingers, 2001; Popp et al., 2024; Prat, 2022).

Although VEs have been explored in military contexts (Caso, 2024; Hays & Vincenzi, 2000; Huff, 2024; McCoy-Fisher et al., 2019; Mouloua et al., 2023; Ross & Gilbey, 2023), theoretical and practical gaps remain, particularly around how best to employ XR VEs to sufficiently replicate the subtle social, spatial, and temporal cues needed in a multi-person environment for learning shiphandling skills. This study addresses those gaps by comparing XR and NSST training facilitation in terms of cognitive workload, system usability, and afforded interactions needed to build bridge team confidence and competence in the exercise of navigation, seamanship and shiphandling skills.

2.2. Research hypotheses

H₁: Knowledge flow facilitated via XR will (for mapped skills and tasks) meet or exceed facilitation provided via a Mockup Trainer.

H₂: Extraneous cognitive load produced by XR will not (for mapped skills and tasks) exceed extraneous cognitive load produced by a Mockup Trainer.

H₃: Facilitation of critical Situational Awareness (SA) skills via XR will meet or exceed skills facilitation via a Mockup Trainer.

H₄: Knowledge acquired via XR will, when preceding Mockup training, complement and enhance performance observed in the Mockup Trainer.

3. Research Design

It's well accepted that physical mockups support immersive, spatial temporal knowledge flow, but research into multi-person XR VEs remains nascent. Given this, the study sought to illuminate whether XR could facilitate distributed cognitive processes across the whole of a bridge environment. ONR's VIBRaNT system, a modified COTS system call VASCO® created by Kilo Solutions UK, hosted the XR VE. This design, informed by *Cognition in the Wild* (Hutchins, 1995) conception of distributed cognition, facilitated a holistic knowledge flow across the entirety of the bridge ecosystem. In this, multi-person explicit, implicit, and tacit flows of knowledge were facilitated but across all components comprising the VE simulation, e.g., bridge controls, sensor systems, displays, communication systems, sound, etc.

Subjective responses from crews assigned to Arleigh Burke Class DDGs were collected after experiencing training in both XR and the NSST. Data consisted of numerical responses to a battery of surveys collected after each training experience (Numeric and Likert Scale 1-7). By comparing paired responses, XR to NSST, an assessment of XR facility to support bridge training was made.

Participants included 28 U.S. Navy bridge teams, comprised of 158 participants, from Naval Station San Diego. Bridge teams were sampled based on convenience, where regularly scheduled training events dictated bridge team assignments for XR testing based on their normally scheduled NSST training events. Bridge team complements varied between 3–7 personnel but once assigned, were held constant in both the XR and NSST conditions.

Bridge team watch standing assignments, e.g., Officer of the Deck (OOD), Junior Officer of the Deck (JOOD), Conning Officer (CONN), etc., were kept constant across training sessions. Experimental (XR) and control (NSST) condition sessions were conducted on the same day “back-to-back” and counterbalanced with 14 bridge teams participating first in the NSST, the other 14 teams participating in XR first.

In Figure 5, bridge team participants trained in the NSST (left) followed by the XR (right). XR HMDs presented the virtual bridge environment, complete with avatar enabled social interaction, marine environmental effects, a bridge audio sound scape, bridge information displays, e.g., RADAR, Voyage Management System, Helm controls, etc. All of this was synchronized to the synthetic external world being presented outside the bridge windows providing an experience of being aboard a real ship.



Figure 5. XR Bridge Trainer versus USN Mockup.
(Author, 2025)

In addition, XR participants, unlike movie goers, had full agency in where to be, what to look at, who to interact with, what equipment to use, and could even ‘look through’ XR facilitated binoculars to magnify distant objects as done in the real world. In the NSST mockup trainer, participants were provided with similar affordances, but had the added advantage of physical touch, seating surfaces, and being able to walk around with other bridge watch standers along with registering facial expressions and emotional responses.

4. Method

A within-subjects experimental design compared XR and NSST survey responses of identical bridge team configurations. Each team completed a similar scenario in both conditions. Shiphandling scenarios were derived from U.S. Navy training protocols and XR scenarios were matched to those protocols. These included Underway Replenishment, Contact Management, Channel Navigation, etc. Training scenarios varied from team to team, but in each case the same scenario was maintained across XR and NSST conditions.

Participants first received standardized pre-briefing instructions and scenario objectives. The control condition utilized the Navigation, Seamanship, and Shiphandling Trainer (NSST) full-scale mockup facility with physical control interfaces and projected simulation. The experimental condition employed ONR’s VIBRaNT system, a COTS-based XR bridge

training VE designed to replicate a DDG’s bridge layout and control interfaces in a fully immersive virtual simulation.

Survey instruments included 1) NASA Task Load Index (TLX) Workload survey, 2) System Usability Scale (SUS) survey and, 3) Bridge Team Training Self-Assessment survey. Additionally, the OOD completed a Self-Assessment survey and the Instructor filled out Bridge Team and OOD Assessment surveys, all of which generated an aggregate response of over 17,274 data points. Response data served as dependent variables, while each training platform or “condition,” XR and NSST, served as independent variables. Survey responses were collected immediately after each training session, XR followed by NSST or NSST followed by XR respectively. All survey questions were identical for each condition, with each participant completing three surveys, except for the OOD and the Instructor who each provided additional responses.

By comparing survey responses of the experimental condition (XR) to the control condition (NSST), an inference was made as to the utility of XR to facilitate knowledge flow for bridge training. In this, there is no absolute measure of “knowledge flow facilitation,” but rather a benchmarked comparison of a novel system (XR) to that of the trusted USN legacy system (NSST).

Each survey instrument provided different, but complementary, lenses to infer knowledge flow facilitation. The NASA TLX survey provided a lens as to the XR cognitive load in relation to the NSST. By comparing responses from XR to the NSST across each TLX measure e.g. “Mental Demand,” “Physical Demand,” “Temporal Demand,” etc., cognitive load produced by XR (relative to the NSST) could be assessed. If a particular TLX measure, i.e., “Mental Demand,” produced higher cognitive load in XR than in the NSST, then knowledge flow facilitation provided by XR was considered lower than that of the NSST. If, on the other hand, responses to a TLX measure, i.e., “Temporal Demand,” produced a lower cognitive load in XR than in the NSST, then the knowledge flow facilitation provided by XR was considered higher (for Temporal Demand) than that of the NSST. This approach was also employed for comparing System Usability Scale (SUS) survey responses and the subsequent assessment surveys.

As with NASA TLX Workload, SUS surveys have been utilized in research for decades and are considered by psychometricians as a highly reliable, empirically validated instrument for determining system utility. Here, as with NASA TLX, SUS is hypothesized as an indicator of knowledge flow facilitation. By measuring SUS responses to the XR system relative to the NSST, an assessment of XR system “usability” for bridge

training can be made. For this comparison, paired responses to each of the ten SUS survey question, i.e., “I thought the system was easy to use,” were compared to determine how “usable” the XR system was relative to the NSST. When a SUS measure for XR compared favorably to the NSST, a positive inference supporting XR facilitated knowledge flow was made, and vice versa.

Both NASA TLX and SUS provided overarching or “meta” indicators of system facilitation, but to look deeper into the specific bridge team training needs, three additional bridge training surveys were created specifically for this study. These instruments, based on Navy training doctrine used in the NSST, included a Bridge Team Training Self-Assessment survey, an OOD Self-Assessment survey, and an Instructor Bridge Team and OOD Assessment survey.

Assessment surveys collected from the bridge team, OOD, and instructor surveys were evaluated in the same way as the NASA TLX and SUS surveys; paired numerical responses (to the same questions posed for both the XR and NSST conditions) were compared. As with the other surveys, when responses in the XR condition were greater than that of the NSST, a positive inference was made regarding XR facilitated knowledge flow. Apart from the OOD and Instructor surveys, results from every survey were compared for “All Participants” and then filtered for comparing results of participants performing the same bridge watch station assignment, i.e., “CONN Only.”

4.1 Statistical analysis approach

The statistical analysis software “ROV BizStats®” was used to evaluate all response data (Mun, 2014). Several different statistics tests were run for each of the surveys implemented. Analysis began by generating descriptive statistics, e.g., mean, median, standard deviation, etc., and then checking for distributional fit, and data normality. Once this was complete, reliability checks were made, followed by different data comparisons to determine results.

4.2 Statistical analysis: data description

Descriptive statistics were generated for each participant response question, i.e., “NASA-TLX Control Condition (NSST) Mental Demand-All Participants.” This included arithmetic mean, median, upper and lower Confidence Intervals (CI), Standard Deviation, Skew, Kurtosis, etc.

A Distributional Fitting analysis was then performed by evaluating the best 10 distributional model “fits” for each response question. To perform this

test, BizStats determined first best fit for a given response question i.e., TLX NSST Mental Demand, which in this case was a “PERT” distribution using an Akaike model and so forth.

After completing the distributional fitting analysis, each data set was evaluated for normality using a Shapiro-Wilk (Royston Algorithm) and D’Agostino-Pearson test. While a few of the data sets, i.e., “NASA TLX Control Condition (NSST) Temporal Demand,” were found to be “plausibly normal”, many were not. Based on this finding, the decision was made to proceed using non-parametric tests.

4.3 Statistical analysis: data reliability

Data reliability was evaluated by checking Internal Consistency Reliability (ICR) and Inter-Rater Reliability (IRR). “Guttman’s Lambda and Split Half Model” was employed to evaluate ICR, and a “Kendall’s W (With Ties)” test was used to evaluate IRR. (“With Ties” was selected as many of the compared control and experimental values ‘tied’ across the distribution.) Although some of the data was found to be plausibly normal, the Inter Class Correlation (ICC) test was not selected as the survey data was deemed ordinal, based on subjective participant responses with no way to judge interval distances from person to person. ICR and IRR tests determined the data to be sufficiently reliable to warrant statistical comparison analysis.

4.4 Statistical analysis: data comparison

To compare each condition, a BizStats “Hotelling T-Square: 2 Variable Dependent Pair with Related Measures” test was run to evaluate the question (across all responses) of each survey, e.g. NASA-TLX, System Usability Scale, Bridge Watch Team Self-Assessment, etc. Tests compared “All Participant” responses to each survey as well as each sub-group with $n > 25$, e.g., “OOD Only”, JOOD Only, CONN Only, etc.

Following this, a “Non-Parametric Wilcoxon Sign-Rank Test (Two Var)” bivariate was employed to compare the control condition (NSST) responses (to each individual question) to those of the experimental condition (VIBRaNT XR). As with the Hotelling T-Square comparison, tests were first run for “All Participants” and then for each sub-group, e.g., “OOD Only,” “JOOD Only,” “CONN Only,” etc., for all surveys including, NASA TLX Workload, System Usability Scale, Bridge Watch Team Self-Assessment, OOD Assessment, Instructor Bridge Watch Team and OOD Assessments. A “Bonferroni Test (Two Variables with Repetition)” was then run on the same response data sets to correct potential p-value errors along with a

simultaneous confidence interval test. Following this, a Principal Component Analysis (PCA) with Varimax Rotation was employed along with a power analysis, to include effect size (Cohen's Delta) determination for each survey question.

Because paired analysis requires “matched pairs”, test samples fell below the total number of participants as some individuals had to depart training sessions early or simply did not provide an answer.

5. Results

The NASA-TLX workload data analysis revealed more similarity than difference across control and experimental conditions. TLX results for “All Participants” presents a comparison of Wilcoxon Signed-Rank Test results for XR (green bars) vs NSST (blue bars) across all six TLX dimensions (Figure 6). The chart reveals only two statistically significant findings. “Performance” was much higher in the NSST, while the TLX measure of “Frustration” was higher in the XR condition. All other factors, mental, physical, temporal demands, and effort were not significantly different from one another. PCA analysis determined TLX subscales organized into components of Cognitive/Task-Demand and Affective/Evaluative Response. Notably, TLX “Frustration” aligned with “Performance” in the NSST but shifted to “Demand” in XR, consistent with a first-time novelty effect.

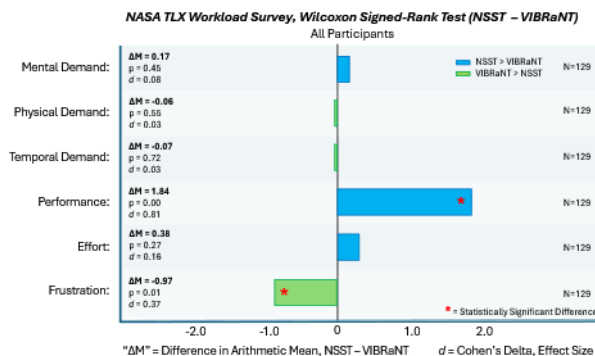


Figure 6. NASA-TLX Results, NSST v XR.

TLX responses for Officers of the Deck (OODs), (Figure 7) suggests more equivalent cognitive loads between the two training conditions. These data indicate that NSST was favored in only one factor, “Performance,” while XR was either insignificantly different from the NSST or trended favorably, as shown in all but two factors, “Performance” and “Effort.”

This shows close alignment with training

expectations for key personnel in decision-making roles. OOD results also held for other watch stations, in every case the support for XR was higher, although different for each watch station, JOOD, CONN, etc.

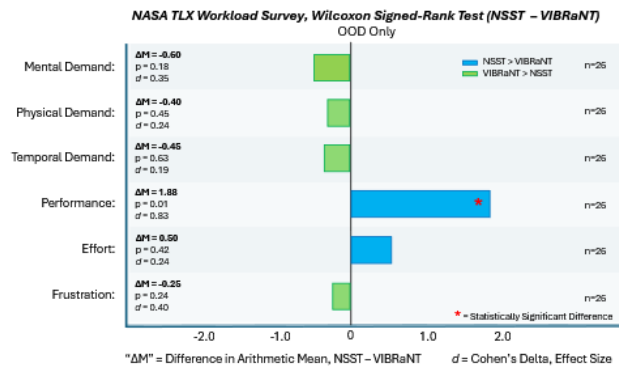


Figure 7. NASA-TLX OOD Results, NSST v XR.

An order effect was also checked (Figure 8). In exit interviews, participants who trained first in XR reported feeling more prepared for their NSST training. However, subsequent Mann-Whitney U tests failed to support this post event interview response. While failing to support a positive XR effect, it did not show a negative effect either, indicating that more research is needed to delineate if XR supports mockup workload response as measured in the TLX instrument.

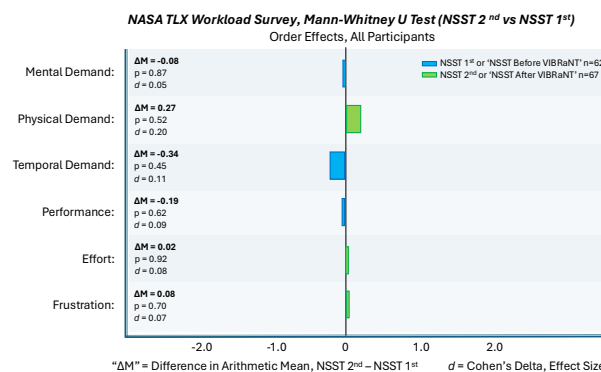


Figure 8. NASA-TLX Order Effect on NSST after using XR v not using XR.

The System Usability Scale (SUS) analysis evaluated ten “usability” statements; 1) “I think that I would like to use this system frequently,” 2) “I found the system NOT unnecessarily complex,” 3) “I though the system was easy to use,” 4) “I would NOT need the support of a technical person to be able to use this system,” 5) “I found the various functions in this system were well integrated,” 6) “I thought there was NOT too

much inconsistency in this system,” 7) “I would imagine that most people would learn to use this system very quickly,” 8) “I found the system NOT very cumbersome to use,” 9) “I felt very confident in the system,” 10) “I did NOT need to learn a lot of things before I could get going with this system.” Results favored NSST (Figure 9) but “perceived ease of use” responses trended towards VIBRaNT XR.

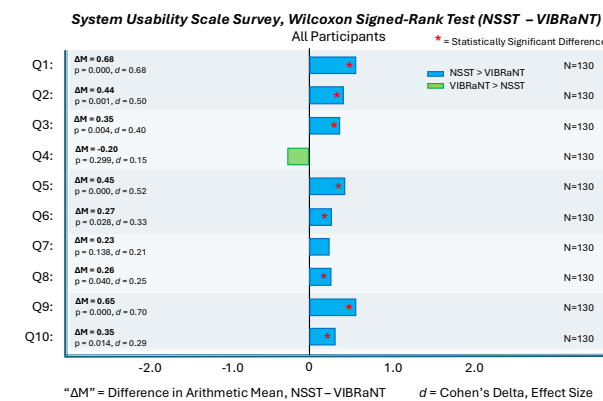


Figure 9. SUS Results, NSST v XR.

When looking at each individual watch stander, i.e., OOD (Figure 10), the picture changes. For the OOD only 3 SUS factors were significantly different.

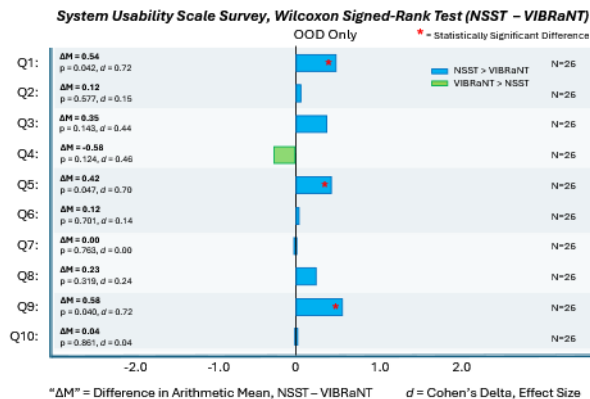


Figure 10. SUS OOD Results, NSST v XR.

Figure 11 illustrates a second-order effect: participants who trained in XR first rated NSST usability more favorably than those who trained in NSST without use of XR. While not statistically significant, it indicates that XR did not have a negative impact on NSST user perceptions.

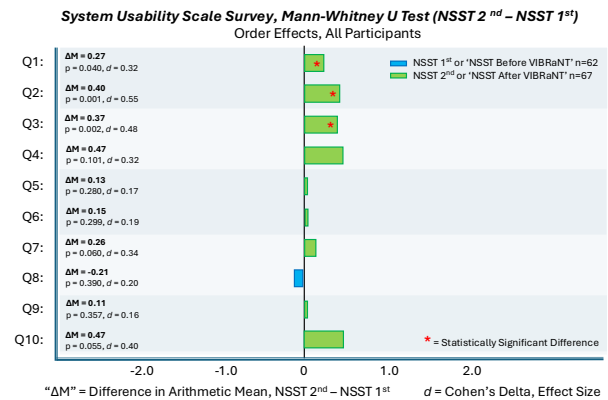


Figure 11. SUS Order Effect, XR first.

Studies have shown men to be more visually inclined, but this was not supported in this research. Figures 12 and 13 show male vs female comparisons.

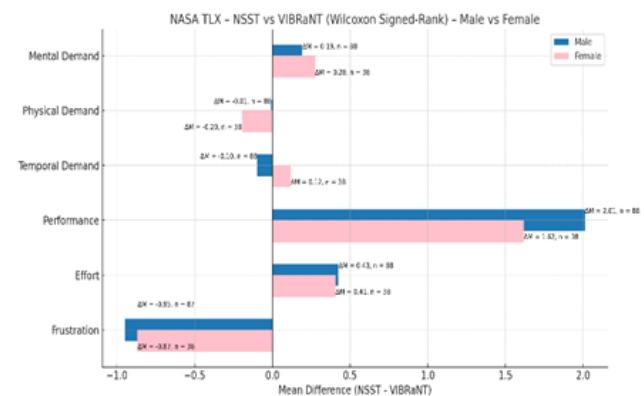


Figure 12. Male v Female NASA-TLX Response.

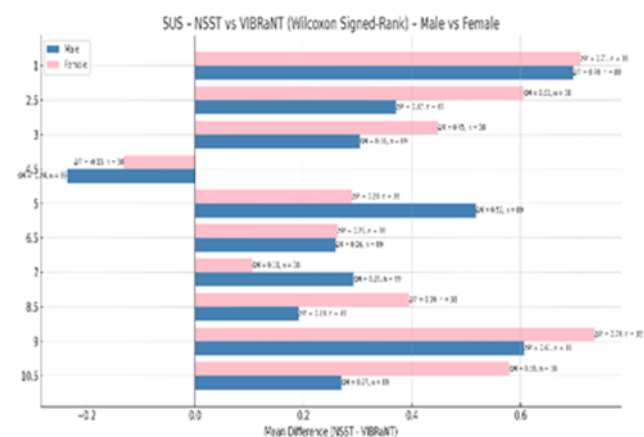


Figure 13. Male v Female SUS Response.

The Bridge Watch Team Self-Assessment (29 questions), OOD Self-Assessment (28 questions), Instructor Assessments for OOD (28 questions) and the Bridge Team Assessment (31 questions) for the Bridge Team) showed a similar pattern to those found

in the TLX and SUS survey analyses. In these, participants responded to “Training Rubric” statements, i.e., “The watch team correctly used standard commands to Conn the ship.” A sample of the results for the Bridge Watch Team Self-Assessment, questions 11 to 20 are provided here as indicative of the overall findings.

The questions/statements (derived from USN instruction CNSP/CNSL INST 3505 1C N7 08FEB22) for this sample are as follows, 11) “I pointed out potential collision / near miss situations,” 12) “I was able to perceive potential dangers,” 13) “My Bridge Team used standard commands to conn the ship,” 14) “My Bridge Team perceived set and drift conditions to conn the ship,” 15) “My Bridge Team foresaw dynamics needed to conn the ship,” 16) “My Bridge Team was able to operate our ship in accordance with COLREGS Rule 2,” 17) “It was easy for me to learn how to use the training system,” 18) “I had no trouble interacting with the simulated VMS,” 19) “I could easily interact with the simulated RADAR,” and 20) “I had no trouble interacting with the simulated Helm / Lee Helm controls.”

The Self-Assessment analysis had some additional limitations in that every question offered the possible response of “N/A”. Depending on the statement posed and the watch station assigned, some of the response pairs could not be analyzed, which lead to varying sample sizes for each question and, in some cases, extremely small sample sizes for different watch standers, noted on the chart in orange.

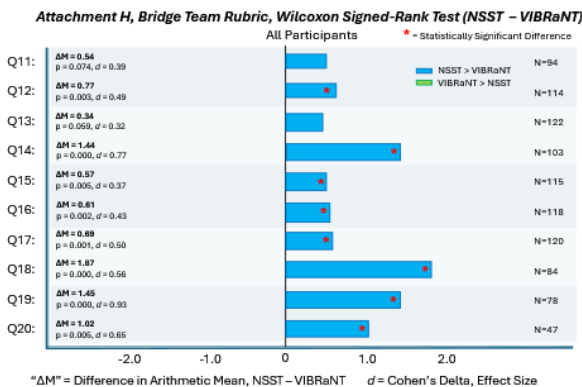


Figure 14. Bridge Team Self-Assessment, Q11- Q20 All Participant Responses.

While the NSST was favored in the “All Participant” responses (Figure 14), fewer statistical differences were found comparing individual watch standers, i.e., OOD responses (Figure 15).

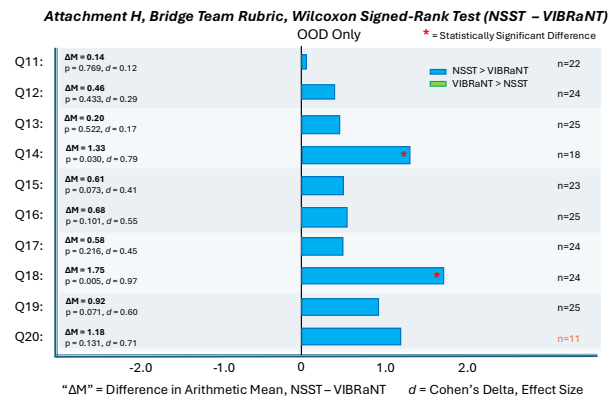


Figure 15. Bridge Team Self-Assessment, Q11-Q20 OOD Only Responses.

6. Discussion

Research findings support three of four alternate hypotheses, specifically:

H₁ was supported by positive SUS results and stable TLX performance and individual training rubric scores, indicating that XR provided comparable knowledge flow facilitation relative to the NSST mockup.

H₂ was upheld by TLX data showing no significant increase in mental, temporal, or physical load—particularly for key decision-makers like OODs.

H₃ received indirect support through stable NASA-TLX and Self-Assessment “Rubric” related scores related to performance and effort, though direct empiric SA metrics, such as eye tracking analysis, remain for future inquiry.

H₄ was supported by order effect perceptions observed in the SUS results, but follow-on study is needed to fully support XR exposure positively influences mockup effectiveness.

These outcomes suggest XR is not only a viable complement to traditional training platforms but may also enhance and extend learning transfer when used as a preparatory tool. The ability to instantiate immersive, spatially accurate VEs that flow tacit knowledge—particularly in distributed team contexts—marks a significant step forward for knowledge management in high-risk domains like naval shiphandling.

The study, however, was not without limitations. As noted, the sample sizes for some of the assessment metrics were low, and in certain cases this produced lower effect sizes and less overall reliability in those

results. Further research is warranted to expand the sample, generate longitudinal data, and measure beyond knowledge flow proxies. Integrating richer behavioral data, scenario-based assessments, and long-term retention measures would aid in fully characterizing XR's contributions to tacit knowledge flow and acquisition.

Another area of research to explore would be the contribution of haptic touch in future iterations of XR. Incorporating physical interaction from items like the ship's wheel and throttle controls was recommended in post event interviews with crew members. AI based agents as bridge watch standers, e.g. CONN, HELM, LEE HELM, etc., could also be explored to provide individual trainees and smaller teams an ability to practice without the entire bridge crew.

The capacity of XR to facilitate tacit knowledge flow among teams—not just individuals—holds promise for training in fields such as aviation, emergency medicine, and nuclear power operations. Where knowledge is experiential, embodied, and distributed, XR can serve as a scalable, immersive platform to simulate realistic team-based dynamics.

7. Conclusion and recommendations

This study concludes that XR offers a viable and effective method for facilitating tacit knowledge flow in Navy bridge training. The evidence suggests that XR-facilitated virtual environments can match and, in some cases, enhance the knowledge transfer typically achieved through traditional NSST mockup systems. Moreover, the experiment, in its ability to set-up a training venue “on the fly” in a spare MSTCPAC classroom demonstrates unique benefits of XR in terms of portability, usability, and its potential to support team-based training anytime and anywhere.

Recommendations include the full development and deployment of an XR bridge training prototype, with appropriate funding and resource allocation to refine the system based on the findings of this study. Particular attention should be given to customizing VEs to match specific ship configurations and to expanding scenario libraries to reflect real-world maritime complexity.

Future research will pursue video and eye-tracking analysis to further explore decision-making and situational awareness in XR conditions. With continued development, XR-based systems can provide scalable, immersive, and cognitively effective training that meets the evolving needs of the U.S. Navy

and other high-reliability organizations.

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