

## Assessing Virtual Reality Head-Mounted Display-Induced Cybersickness in Simulated Maritime Dynamic Environments

**Ethan Williams, Charles Rowan, Perry McDowell**  
Naval Postgraduate School  
Monterey, CA  
[ethanjwilliams99@gmail.com](mailto:ethanjwilliams99@gmail.com),  
[charles.rowan@nps.edu](mailto:charles.rowan@nps.edu), [mcdowell@nps.edu](mailto:mcdowell@nps.edu)

**Jonathan Vogl**  
US Army Aeromedical Research Laboratory  
Fort Novosel, AL  
[jonathan.f.vogl.civ@health.mil](mailto:jonathan.f.vogl.civ@health.mil)

### ABSTRACT

The U.S. Navy is increasingly incorporating immersive technologies such as virtual reality (VR) head-mounted displays (HMDs) for training and operational use at sea. However, the impact of shipboard motion on VR HMD-induced cybersickness remains underexplored. This study investigates whether VR HMD users experience greater cybersickness in simulated dynamic maritime environments compared to static, land-based settings. A within-subjects design was used with 32 participants completing VR tasks across four conditions: a static, land-based environment and three simulated maritime conditions replicating calm, moderate, and rough sea states. Cybersickness symptoms were measured using the Simulator Sickness Questionnaire (SSQ) and physiological data including heart rate (HR), heart rate variability (HRV), and galvanic skin response (GSR). Results revealed significantly greater SSQ scores and physiological arousal in dynamic, simulated shipboard conditions. These findings suggest that ship motion intensifies cybersickness symptoms, which may impact VR HMD effectiveness at sea. The study provides empirical evidence to inform U.S. Navy decisions about immersive system integration and recommends further work to develop mitigation strategies and adapt VR systems for shipboard use.

### ABOUT THE AUTHORS

**Ethan Williams** is a Lieutenant Junior Grade in the United States Navy. He is a Cryptologic Warfare Officer attached to CWMA-61 out of Ft. Meade, MD serving as a direct support officer to the U.S. Navy's nuclear submarine force. He is a 2022 graduate of the United States Naval Academy and a 2025 graduate of the Naval Postgraduate School.

**Lieutenant Colonel Charles Rowan, PhD**, is a U.S. Army Simulation Operations Officer serving as the Director of the Modeling, Virtual Environments, and Simulation (MOVES) Institute at the Naval Postgraduate School in Monterey, CA. He is a graduate of the United States Military Academy at West Point, NY and the Naval Postgraduate School.

**Perry McDowell** is a Faculty Associate for Research at the MOVES Institute. Mr. McDowell is a graduate of the United States Naval Academy and the Naval Postgraduate School.

**Jonathan Vogl** is a research psychologist at the US Army Aeromedical Research Laboratory at Fort Novosel, AL. Mr. Vogl is a graduate of South Dakota State University and the University of South Dakota.

Sections of this paper were previously published as a thesis by LTJG Ethan J. Williams, USN, at the Naval Postgraduate School.

# Assessing Virtual Reality Head-Mounted Display-Induced Cybersickness in Simulated Maritime Dynamic Environments

Ethan Williams, Charles Rowan, Perry McDowell  
Naval Postgraduate School  
Monterey, CA  
[ethanjwilliams99@gmail.com](mailto:ethanjwilliams99@gmail.com),  
[charles.rowan@nps.edu](mailto:charles.rowan@nps.edu), [mcdowell@nps.edu](mailto:mcdowell@nps.edu)

Jonathan Vogl  
US Army Aeromedical Research Laboratory  
Fort Novosel, AL  
[jonathan.f.vogl.civ@health.mil](mailto:jonathan.f.vogl.civ@health.mil)

## INTRODUCTION

### Background

The U.S. Navy increasingly relies on virtual reality (VR) head-mounted displays (HMDs) to enhance operational training and readiness. These systems provide immersive, scalable, and cost-effective environments for mission rehearsal and skill development. However, while land-based VR applications have shown promise, their use in dynamic maritime environments introduces new human-system integration challenges. Specifically, the motion experienced aboard ships may interact with VR visual stimuli to trigger cybersickness—a form of motion sickness characterized by nausea, disorientation, and oculomotor strain (Kennedy et al., 1993; LaViola, 2000). The Department of the Navy continues to invest in immersive technologies for Fleet-wide application, yet there remains limited understanding of how underway ship motion may compromise their effectiveness or safety at sea.

### Problem Statement

Most cybersickness research has been conducted in static, land-based settings. As a result, the physiological and perceptual impacts of shipboard motion on VR users remain underexplored. Without operationally representative data, the U.S. Navy risks deploying training systems that may degrade cognitive performance, increase fatigue, or pose health risks in underway conditions. There is a clear need to quantify how real-world sea state motion affects cybersickness in VR and to identify factors that may influence individual susceptibility aboard U.S. Navy vessels.

### Research Questions

This study is guided by three core research questions:

1. To what extent does cybersickness experienced by VR HMD users differ between static, land-based settings and simulated dynamic, maritime-based settings?
2. To what extent do individual differences—such as prior experience with immersive technology or experience underway on a U.S. Navy ship—influence susceptibility to cybersickness in static versus dynamic motion environments?
3. To what extent are objective physiological measures correlated with subjective cybersickness symptoms?

### Research Approach

To assess the effects of simulated maritime motion on VR-induced cybersickness, the study employed a within-subject experimental design using a telemetry-driven motion platform with immersive VR tasking. Thirty-two participants completed four exposure conditions representing increasing sea states: static (land-based), calm, moderate, and rough. Each condition featured identical VR content, allowing direct comparison of symptom progression across motion intensities. Subjective symptoms were captured using the Simulator Sickness Questionnaire (SSQ), while physiological responses—including heart rate (HR), heart rate variability (HRV), and galvanic skin response (GSR)—were continuously collected throughout exposure.

## **Implications of Research**

This study contributes to the U.S. Navy's growing body of research on immersive VR systems by addressing a critical human factors challenge—cybersickness—within simulated shipboard environments. As the naval services increasingly adopt HMD-based VR for distributed and underway training, understanding how dynamic maritime motion impacts user tolerance is essential. While prior studies have examined cybersickness in static settings or while using non-immersive displays, this research modernizes that work by integrating both physiological and subjective metrics to evaluate user responses under ship-representative motion conditions with contemporary VR. By examining symptom escalation across sea states and highlighting individual variability in susceptibility, the study informs future design and deployment of motion-aware VR systems. Additionally, findings may influence Fleet policies regarding crew readiness assessments, exposure thresholds, and adaptive system features to safeguard performance and training effectiveness during VR use aboard U.S. Navy vessels.

## **LITERATURE REVIEW**

### **Head-Mounted Displays in the Military: Past, Present, and Future**

The use of HMDs in military contexts has evolved over decades, from analog targeting systems such as the Visual Target Acquisition System (VTAS) and the Integrated Helmet and Display Sight System (IHADSS) to the cutting-edge Gen III F-35 helmet, which integrates visual tracking, augmented overlays, and battlefield telemetry into the pilot's field of view (Bayer et al., 2009). More recently, VR HMDs have seen expanded use across training domains—supporting applications from shipboard suicide prevention modules (DuBois, 2023) to medical rehabilitation, aircraft maintenance, and tactical readiness. Projections indicate that by 2025, over 60% of military training will integrate immersive HMD-based simulations (Vrgal, 2024).

### **Cybersickness**

Despite their advantages, HMDs, especially VR, can trigger cybersickness—a condition resembling traditional motion sickness, with several proposed causes including sensory conflict (LaViola, 2000), postural instability (Riccio & Stoffregen, 1991), and neural mismatch theories (Reason & Brand, 1975). Symptoms span multiple domains, including nausea, disorientation, headaches, and visual fatigue. These symptoms are influenced by hardware characteristics such as field of view and refresh rate, environmental context, and individual traits such as prior VR exposure, age, and sex (Stanney et al., 1997). Given these multisensory symptoms and their variability across users, tools like the SSQ have become essential for standardizing symptom assessment. Although the SSQ remains the standard for symptom assessment, recent research suggests that integrating physiological measures such as GSR and HRV to obtain objective markers of user discomfort can provide a more comprehensive assessment of cybersickness symptoms (Setiowati et al., 2020; Seong & Park, 2024).

Individual differences, particularly prior to VR experience or motion sickness history, may moderate cybersickness risk. Literature indicates that repeated VR exposure can reduce susceptibility through habituation, improving postural stability, and decreasing symptom severity (Weech et al., 2019). Prior gaming or VR experience is often associated with lower cybersickness, as users develop tolerance to sensory mismatches (Chang et al., 2020). However, this effect may not generalize to dynamic environments, where novel motion cues could override prior adaptation. Motion sickness history remains a strong predictor, with susceptible individuals experiencing heightened symptoms (Garrido et al., 2022).

### **Cybersickness in Static versus Dynamic, Naval Environments**

While most research on cybersickness has been conducted in static, land-based virtual environments, operational naval contexts involve dynamic motion that may exacerbate symptoms. However, few empirical studies have examined this contrast directly. One notable effort by Muth and Lawson (2003) involved placing a desktop simulator aboard a ship operating in calm seas to evaluate simulator sickness effects. While foundational, their study was limited by low simulator fidelity, the absence of physiological measurements, and minimal sea state motion. Recent studies have advanced this area, demonstrating that dynamic VR environments elicit stronger cybersickness than static ones, particularly in maritime settings where ship motion amplifies sensory conflicts (Caserman et al., 2021). For instance, at-sea use of augmented reality (AR) HMDs has been shown to induce cybersickness due to vestibular-visual

mismatches (Champney et al., 2024). Additionally, tracking motion sickness in dynamic VR using Electrodermal Activity (EDA) signals highlights interval-based symptom progression in moving platforms (Seong & Park, 2024). Given advances in motion simulation, immersive VR, and physiological monitoring, it is essential to reexamine cybersickness in more representative, dynamic maritime conditions.

## Hypotheses

This study builds on the foundations of Muth & Lawson (2003) by implementing modern VR HMDs, using telemetry-driven motion simulation, and capturing both subjective and physiological markers. It hypothesizes that (1) cybersickness will intensify with increasing maritime motion severity, (2) prior VR or shipboard experience will be associated with less severe symptoms, and (3) physiological metrics, HRV and GSR, will be significantly correlated with SSQ scores, with  $r \geq \pm 0.30$  per Cohen's (1988) benchmark for medium effect sizes.

## METHODOLOGY

This study employed a repeated-measures, within-subjects design to evaluate the effects of simulated ship motion on cybersickness induced by HMD-based VR exposure. Each of the 32 participants completed four trials: one static land-based baseline and three motion-enabled trials corresponding to calm, moderate, and rough sea states. The simulated motion was delivered through a DOF Reality P3 Universal motion platform. Input motion data sent to the platform via telemetry and User Datagram Protocol (UDP) packets included real-world, validated sea trial data collected and shared via NSWC Carderock, a naval research laboratory in Bethesda, MD. The order of exposure was randomized via Latin square design to control for order effects, and each participant served as their own control. SSQ scores and physiological markers were collected across all four conditions and subsequently compared. Baseline data were collected at the start of each session for both subjective and physiological measures. This included administration of the SSQ to screen for pre-existing symptomology and continuous recording of resting-state GSR, HR, and HRV. Participants were only eligible to continue if they exhibited low SSQ scores and physiologically stable baselines, ensuring that all observed symptom changes could be attributed to the experimental motion exposures rather than confounding factors.

### Pilot Study

Prior to the main experiment, a pilot study involving three subjects was conducted to determine safe and effective exposure durations. Pilot participants reported the onset of symptoms—including oculomotor fatigue and mild nausea—within the first 45 to 60 seconds of dynamic VR exposure. Consequently, dynamic trial durations were limited to two minutes to avoid adverse effects while preserving fidelity. The static condition was set to six minutes to match the total exposure time across dynamic trials. All other aspects of the original experimental design were validated by the pilot study procedure.

### Participants

Thirty-two individuals (87.5% active-duty military) participated, with ages ranging from 25 to 53 years ( $M = 34.2$ ,  $SD = 7.85$ ). The participant pool was representative of the fleet demographic targeted for future VR HMD deployment. Over half (65.6%) had prior VR experience, and 53.1% had previously served aboard ships underway. The military participants represented various U.S. services (Navy, Army, Marine Corps) and international partners, with diverse occupational specialties such as logistics, artillery, surface warfare, and IT support. Ranks ranged from O-2 to O-5, and service lengths varied from two to 24 years. No participants reported prior conditions that would contraindicate exposure to VR or motion simulation.

## Materials and Equipment

The immersive VR environment was delivered using the Meta Quest 3 standalone HMD. The Meta Quest 3 was chosen for its high resolution (2064 × 2208 pixels per eye), low latency, and wireless operation, reducing external hardware interference. Meta Quest 3 also represents the top-of-the-line commercial-off-the-shelf VR HMD, thereby serving as a validated system worthy of DoD acquisition consideration. Participants used two Touch Plus controllers to interact with the SimplePlanes VR flight simulator, which was selected for its consistent visual flow and low cognitive workload, enabling the isolation of objective and subjective effects to the change in environmental motion alone rather than the increased complexity of the VR tasking.

Ship motion was simulated using a DOF Reality P3 3-DOF motion platform driven by real-world telemetry data from DDG-1000 sea trials. Sim Racing Studio software was programmed to convert telemetry data into precise pitch, roll, and heave instructions, replicating conditions aligned with WMO-defined calm (Sea States 1-2), moderate (Sea State 3-4), and rough (Sea State 5-6) levels.

Physiological data collection included GSR measured using a Shimmer3+ GSR module and cardiovascular data collected via a Polar H10 chest strap, capturing both HR and HRV metrics with millisecond-level precision. GSR was parsed into tonic (slow baseline changes) and phasic (event-driven, acute bursts) components for analysis. Figure 1 shows the experimental set up.



**Figure 1. Experimental Setup.**

## Procedure

Participants completed all four exposure conditions during a single session. Each session began with a pre-brief, informed consent, and baseline screening that included administration of the SSQ and collection of resting-state physiological data (GSR, HR, and HRV). Participants were only eligible to continue if their pre-exposure SSQ scores were equal to zero and physiological baselines were stable, ensuring they were symptom-free prior to exposure.

Each trial required participants to complete a short VR training session involving sustained visual focus, moderate controller input, and continuous dynamic orientation. After completing each experimental condition, participants were provided a three-minute rest break to allow for symptom recovery, hydration, and confirmation of readiness before the next exposure. At the end of each condition, participants completed the SSQ again, and physiological data were saved for post-processing. Environmental conditions were held constant across all trials, including lighting, temperature, headset fit, and posture.

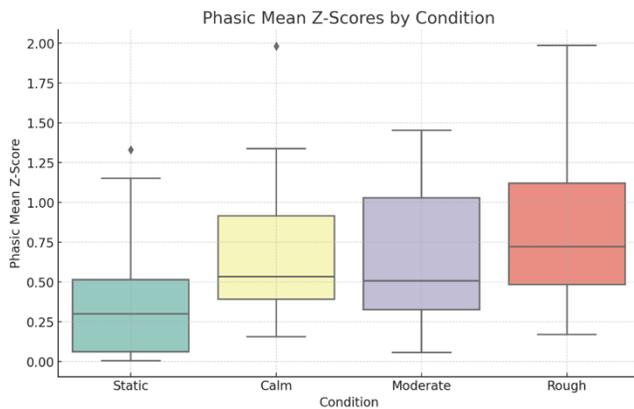
## RESULTS

### Galvanic Skin Response

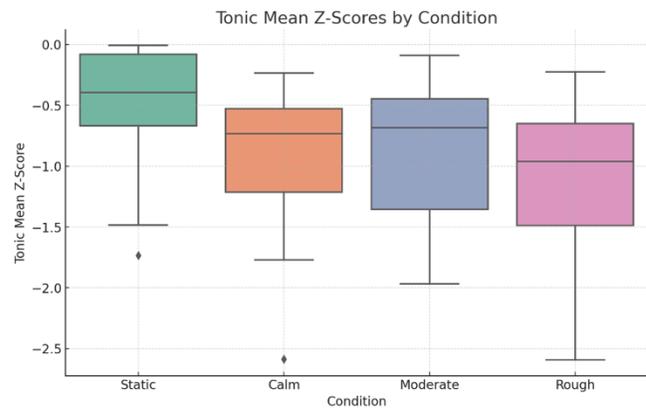
To comprehensively assess participants' GSR markers across the four conditions of the study, two different metrics were analyzed: tonic levels and phasic levels. The tonic component—represented by the mean skin conductance level (SCL)—reflects sustained sympathetic nervous system activity and serves as an indicator of baseline arousal over time. Elevated tonic levels have been linked to prolonged emotional and physiological arousal, consistent with the expected effects of VR-induced cybersickness (Boucsein, 2012). In contrast, the phasic component captures short-term and transient fluctuations in GSR and is represented as skin conductance responses (SCRs). These phasic responses provide insight into the intensity of immediate reactions to stimuli and reflect more acute arousal rather than ongoing arousal like its tonic counterpart. Higher SCR amplitudes are associated with strong bursts of emotional and physical responses (Boucsein, 2012). By incorporating both tonic and phasic components, consistent with Seong and Park (2024), the study aimed to capture both sustained and sudden changes in GSR activity.

The analysis of the GSR data revealed significant differences in both tonic and phasic GSR levels across the four experimental conditions, originally measured in microsiemens and subsequently normalized within each participant's dataset prior to signal decomposition. The resulting tonic and phasic mean Z-scores were then averaged across subjects for each condition.

The tonic mean Z-scores showed a progressive decrease from the static condition ( $0.615 \pm 0.643$ ) to the dynamic rough condition ( $-1.116 \pm 0.667$ ) suggesting increased baseline arousal with greater motion intensity. Similarly, phasic mean Z-scores increased from static ( $0.475 \pm 0.496$ ) to rough ( $0.845 \pm 0.520$ ) indicating that transient, stimulus-driven arousal also intensified through the dynamic conditions. Figures 2 and 3 plot the Z-score results.



**Figure 2. Phasic Mean Z-Scores by Condition.**



**Figure 3. Tonic Mean Z-Scores by Condition.**

### Heart Rate and Heart Rate Variability

A repeated measures ANOVA showed a significant effect of condition on HR ( $F(3, 93) = 14.10, p < 0.001$ ), indicating that HR differed significantly across the static and dynamic calm, moderate, and rough conditions. However, paired t-tests comparing static to each individual dynamic condition revealed mixed results: static vs. calm ( $t = -2.15, p = 0.040$ ), static vs. moderate ( $t = -1.44, p = 0.161$ ), and static vs. rough ( $t = -4.81, p < 0.001$ ). These results indicate that HR was significantly elevated in calm and rough conditions compared to static, but not so when comparing static vs. moderate. The strong increase in HR under rough conditions shows a clear physiological response aligned with increased cybersickness symptoms. The mixed results may reflect varying levels of physiological adaptation or tolerance among participants to lower levels of motion. While calm conditions induced a modest, yet significant, HR increase, moderate conditions did not reach significance. This could possibly be due to individual variability in reaction to motion intensities. In contrast, simulated dynamic rough sea states elicited heightened arousal, as evidenced by the statistically significant HR elevation.

HRV, specifically the root mean square of successive differences (RMSSD), was analyzed to capture parasympathetic responses to the changing of environmental motion for users in VR. Decreased HRV typically reflects increased physiological stress (Shaffer & Ginsberg, 2017). A repeated measures ANOVA showed no significant effect of condition on HRV,  $F(3,93) = 0.23, p = 0.88$ . Similar to HR, paired t-tests comparing static to each dynamic condition confirmed no significant differences: static vs. calm ( $t = 1.20, p = 0.24$ ), static vs. moderate ( $t = 0.37, p = 0.71$ ), and static vs. rough ( $t = -0.31, p = 0.76$ ). These results suggest that HRV remained relatively stable across the experimental conditions.

### Simulator Sickness Questionnaire Scores

The SSQ was administered immediately following each of the four VR exposure conditions—static, calm, moderate, and rough—to assess participants' symptom severity. Each SSQ was scored according to the method developed by Kennedy et al. (1993), which calculates weighted subscale scores for Nausea (N), Oculomotor (O), and Disorientation (D), then aggregates them into a Total Score. Subscale scores were computed by averaging symptom ratings (ranging

0–3) across relevant items, applying the respective weightings (N: 9.54, O: 7.58, D: 13.92), and multiplying the sum of each raw subscale result by 3.74 for the Total SSQ Score.

SSQ results revealed a clear and substantial increase in simulator sickness symptoms as motion intensity increased. The mean Total SSQ Score rose from 9.58 (SD = 14.75) in the static baseline condition to 20.92 (SD = 25.93) in calm seas, 29.60 (SD = 31.25) in moderate seas, and 41.37 (SD = 41.35) in the rough sea state—representing a more than fourfold increase from static to rough. Each subscale demonstrated a similar trend. The Nausea subscale increased from 6.26 (SD = 10.73) in static to 16.10 (SD = 22.40) in calm, 22.66 (SD = 24.08) in moderate, and 34.58 (SD = 33.04) in rough. Oculomotor scores rose from 8.29 (SD = 13.66) in static to 14.45 (SD = 18.60) in calm, 20.37 (SD = 24.69) in moderate, and 28.42 (SD = 32.79) in rough. Disorientation, the most sensitive subscale, climbed from 10.00 (SD = 17.04) in static to 25.66 (SD = 34.30) in calm, 36.10 (SD = 42.55) in moderate, and 48.28 (SD = 52.30) in the rough sea state. Table 1 presents SSQ score summary statistics.

**Table 1. Simulator Sickness Questionnaire Summary Statistics by Subscore**

| Condition     | (N)<br>Mean | (N)<br>SD | (O)<br>Mean | (O)<br>SD | (D)<br>Mean | (D)<br>SD | Total<br>Score<br>Mean | Total<br>Score<br>SD |
|---------------|-------------|-----------|-------------|-----------|-------------|-----------|------------------------|----------------------|
| Static, Land  | 6.26        | 10.73     | 8.29        | 13.66     | 10.0        | 17.04     | 9.58                   | 14.75                |
| Calm Seas     | 16.1        | 22.40     | 14.45       | 18.60     | 25.66       | 34.30     | 20.92                  | 25.93                |
| Moderate Seas | 22.66       | 24.08     | 20.37       | 24.69     | 36.1        | 42.55     | 29.60                  | 31.25                |
| Rough Seas    | 34.58       | 33.04     | 28.42       | 32.79     | 48.28       | 52.30     | 41.37                  | 41.35                |

A repeated measures ANOVA was performed for each subscale and the Total SSQ Score to determine whether these increases were statistically significant. Results confirmed significant effects of motion condition across all four metrics: the Nausea scale yielded  $F(3, 93) = 31.89, p < 0.001$ ; Oculomotor symptoms showed  $F(3, 93) = 15.50, p < 0.001$ ; Disorientation scores produced  $F(3, 93) = 17.86, p < 0.001$ ; and the Total SSQ Score had  $F(3, 93) = 25.45, p < 0.001$ . These results demonstrate a statistically significant increase in simulator sickness symptoms as a function of motion intensity, with the most severe symptoms occurring during the rough sea condition across all domains. Given the ordinal motion conditions and evident progressive trend in means, post-hoc pairwise comparisons beyond planned contrasts (static vs. each dynamic) were not conducted to minimize Type I error risk.

In addition to within-subject effects of motion condition, between-group comparisons were conducted to assess whether prior experience with VR or shipboard operations influenced cybersickness severity. Independent-sample *t*-tests revealed that participants with prior VR experience reported significantly higher Oculomotor SSQ scores under both moderate ( $t(30) = -2.13, p = 0.041$ ) and rough ( $t(30) = -2.35, p = 0.025$ ) sea state conditions compared to those without prior VR exposure. This pattern suggests greater visual sensitivity or symptom awareness among experienced users. For the Nausea and Disorientation subscales, however, no statistically significant differences emerged based on VR experience at any motion condition.

Conversely, participants with prior underway shipboard experience generally reported lower SSQ scores than those without such experience, although most differences did not reach statistical significance. A near-significant reduction was observed for Total SSQ scores in the moderate condition ( $t(30) = 1.95, p = 0.060$ ), suggesting a possible protective effect of prior motion habituation. While these group-level differences did not alter the overall trend of increasing SSQ severity with motion intensity, they indicate that individual experience factors may modulate symptom expression, particularly in high-motion environments.

### Correlation Analysis

To investigate the relationship between subjective measures of cybersickness and objective physiological markers, a series of statistical techniques were applied to the data. A correlation matrix was generated by calculating Pearson correlation coefficients to explore the basic relationships between Total SSQ Scores and each physiological variable: tonic mean Z-scores, phasic mean Z-scores, mean HR, and HRV. The results indicated a moderate positive correlation between Total SSQ Scores and HRV ( $r = 0.372$ ) and a weaker positive relationship between Total SSQ Scores and phasic mean Z-scores ( $r = 0.233$ ). A negative correlation was observed between Total SSQ Scores and tonic mean Z-scores ( $r = -0.235$ ), while mean HR showed a weaker correlation ( $r = 0.131$ ) with Total SSQ Scores. Figure 4 shows the correlation matrix.

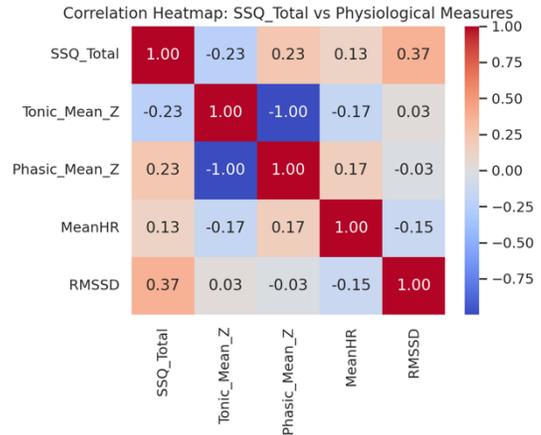


Figure 4. Correlation Heatmap.

Next, an ordinary least squares (OLS) regression was performed to model Total SSQ scores as a function of the physiological variables. The model accounted for 22.5% of the variance in Total SSQ scores ( $R^2 = 0.225$ ). HRV emerged as a statistically significant predictor ( $p < 0.001$ ), while the other predictors were not significant at conventional thresholds.

Table 2. Ordinary Least Squares Regression Results

| Variable            | Coefficient | Std. Error | t Value | P> t  |
|---------------------|-------------|------------|---------|-------|
| Intercept           | -108.783    | 64.183     | -1.695  | 0.093 |
| Tonic Mean Z-Score  | -285.372    | 320.026    | -0.892  | 0.374 |
| Phasic Mean Z-Score | -330.164    | 414.236    | -0.797  | 0.427 |
| Mean HR             | 1.688       | 0.891      | 1.895   | 0.060 |
| HRV (RMSSD)         | 787.478     | 157.337    | 5.005   | 0.000 |

To further explore whether physiological markers varied significantly across different motion conditions, repeated measures ANOVA tests were conducted separately for each measure. The results revealed significant differences in mean HR ( $F(3,93) = 14.21, p < 0.001$ ), tonic GSR ( $F(3,93) = 6.30, p < 0.001$ ), and phasic GSR ( $F(3,93) = 5.89, p < 0.001$ ) across conditions. In contrast, RMSSD did not significantly vary with condition ( $F(3,93) = 0.54, p = 0.65$ ), indicating that HRV remained relatively stable irrespective of environmental changes.

Recognizing the possibility of non-linear relationships, a quadratic regression model was tested to examine the link between HRV (RMSSD) and SSQ scores. This model accounted for a greater proportion of variance ( $R^2 = 0.256$ ) compared to the linear model. Both the linear and squared terms of HRV were significant, with HRV ( $\beta = -952.12, p = 0.021$ ) and  $HRV^2$  ( $\beta = 6141.26, p < 0.001$ ), suggesting that subjective sickness increases at both low and high extremes of HRV. Figure 5 shows a quadratic relationship between Total SSQ and HRV.

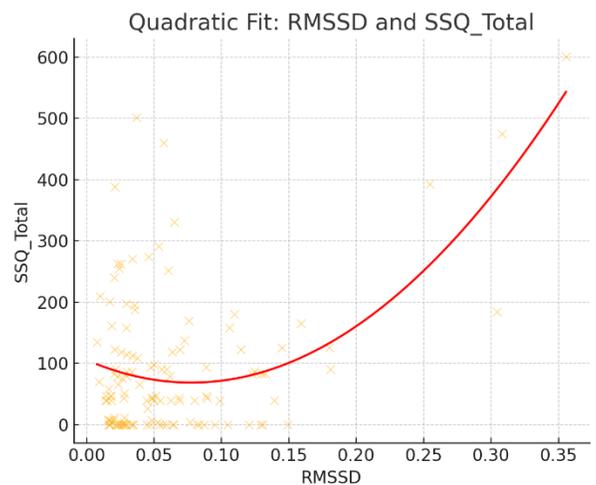


Figure 5. Quadratic Regression

## DISCUSSION

This study examined the differential effects of VR-induced cybersickness under static versus simulated maritime motion conditions, with the aim of informing the integration of HMDs aboard U.S. Navy vessels. By employing both subjective (SSQ) and objective (HR, HRV, GSR) measures, the results confirmed that dynamic motion environments significantly exacerbate cybersickness symptoms, validating the need for mitigation strategies in operational use.

### Research Questions and Hypotheses Evaluation

Three research questions guided this work: (1) To what extent does cybersickness experienced by VR HMD users differ between static, land-based settings and simulated dynamic, maritime-based settings? (2) To what extent do individual differences—such as prior experience with immersive technology or experience underway on a U.S. Navy ship—influence susceptibility to cybersickness in static versus dynamic motion environments? (3) To what extent are objective physiological measures correlated with subjective cybersickness symptoms?

*Hypothesis 1* predicted that dynamic maritime motion would elevate cybersickness severity compared to static conditions. This was supported by statistically significant increases in Total SSQ scores, all SSQ subscores, and elevated HR and GSR responses under dynamic exposure. Symptoms were most pronounced in the rough condition, demonstrating that the motion profile typical of U.S. Navy vessels underway intensifies the user's sympathetic nervous system response and subjective discomfort.

*Hypothesis 2* proposed that prior VR or underway experience would attenuate symptom severity. This was not supported. Participants with prior VR exposure reported higher oculomotor discomfort, and underway experience did not significantly affect symptom levels. These findings suggest that prior experience alone does not protect against VR-induced cybersickness and may in some cases increase visual sensitivity, contrasting with general literature trends but highlighting context-specific effects in dynamic settings.

*Hypothesis 3* predicted that physiological signals (HRV and GSR) would correlate with subjective symptom severity. This was partially supported. HRV showed a moderate positive correlation with Total SSQ scores ( $r = 0.372$ ), and a quadratic model revealed that both high and low HRV values corresponded with increased symptom severity. GSR measures, while responsive to motion intensity, were not strong predictors of SSQ scores. Notably, HR increased significantly with motion intensity, and GSR fluctuated with condition severity, reinforcing their roles as general arousal indicators even if not directly predictive of SSQ self-reports.

### Implications

Findings emphasize that VR systems used successfully on land may not translate directly to shipboard contexts without adaptation. Significant symptom escalation in dynamic conditions calls for mitigation protocols before fielding HMDs at sea. This includes pre-use screenings to assess cybersickness resilience, adaptive VR systems that modify visual parameters in real time, and command-level recognition of cybersickness as a planning factor.

### Operational Applications of HRV Monitoring

HRV emerged as a robust predictor of subjective symptoms, suggesting its utility for real-time monitoring in operational settings. Adaptive VR systems could leverage HRV (and GSR) to detect early arousal, automatically adjusting content—for example, reducing optical flow or field of view—to mitigate symptoms (Islam et al., 2020). AI-driven frameworks could personalize experiences based on physiological baselines, enhancing training efficacy aboard ships (Reyero Lobo & Perez, 2022; Dennison & D'Zmura, 2025). The U.S. Navy could incorporate such metrics into VR-based training pipelines to optimize learning while minimizing performance degradation. Operationally, the strong performance of HRV as a predictor suggests that real-time physiological monitoring could inform exposure duration, recovery timing, or automated system adjustments.

### Actionable Mitigation Strategies for Shipboard VR Training

- **Physiological Monitoring:** Implement wearable sensors for HRV/GSR to trigger alerts or content pauses when thresholds are exceeded.

- **Adaptive Content Adjustments:** Use AI to dynamically reduce motion intensity, field of view, or visual complexity in higher sea states.
- **Habituation Protocols:** Pre-assess crew susceptibility; limit VR use during rough seas and enforce recovery breaks.
- **Hardware Optimization:** Select low-latency, high-refresh rate HMDs; incorporate grounding cues like virtual horizons.

The counterintuitive finding that VR-experienced individuals reported more oculomotor strain opens new research directions. It may suggest that acclimated users are more attuned to subtle discomfort, or that adaptation to land-based VR environments does not generalize well to motion-enhanced contexts. Similar trends have been noted in earlier studies, where experienced users exhibited heightened visual sensitivity due to greater familiarity with stabilized virtual environments (Stanney et al., 2003; Rebenitsch & Owen, 2016). This finding could inform the development of novel VR desensitization or resilience training modules tailored for underway deployment, where shipboard motion is a persistent and unavoidable stressor.

### **Methodological Comparisons**

This study used the Meta Quest 3 for its wireless operation and high resolution, minimizing interference in dynamic simulations. However, trade-offs exist with other HMD platforms: for example, Varjo XR-3 offers superior resolution but is tethered, potentially restricting mobility at sea; HTC Vive provides robust tracking but higher latency in wireless modes. Extended Reality (XR) systems (blending VR/AR) may reduce cybersickness by anchoring users to real-world visuals, though they trade immersion for stability (Lawson & Stanney, 2021). Non-HMD VR (desktop simulators) avoids head-tracking mismatches but lacks full immersion, limiting naval training fidelity. Future work should compare maritime-specific scenarios (e.g., ship deck tasks) to neutral ones (e.g., static flights) to isolate motion-induced causes.

### **Limitations**

The study's findings are limited by a relatively homogenous sample of mid-career officers, short exposure durations, and a laboratory environment that, while motion-validated, did not fully replicate shipboard variability. Additional work is needed to test longer exposures, more cognitively demanding tasks, and broader demographic groups, including enlisted Sailors. Moreover, only one HMD platform (Meta Quest 3) was tested, limiting generalizability across commercial systems. Future studies should explore XR vs. pure VR for maritime use.

### **Future Work**

Future efforts should explore how prolonged exposure impacts adaptation, whether HRV-based threshold alerts can be operationalized, and whether mitigation strategies—such as automatic visual adjustments or modified training schedules—can be implemented at scale. Comparative testing across hardware platforms and sea states, as well as incorporating cognitive workload variables, would further advance this research. Ultimately, physiological data streams could drive real-time adaptation in VR content delivery to maintain training effectiveness while safeguarding user health. Comparative testing of HMD platforms and scenario types as noted above will help refine these approaches for operational maritime environments.

### **CONCLUSION**

This research offers a comprehensive assessment of cybersickness in dynamic maritime environments, providing strong evidence that VR use aboard ships introduces operational risk if unmitigated. By quantifying the physiological and subjective impacts of shipboard motion on immersive system users, the study supplies the empirical foundation for Navy decision-makers, system developers, and training designers to adapt future VR deployments for maritime success. As HMD technology continues to expand in military use, these insights ensure that its integration enhances rather than hinders warfighter readiness.

### **ACKNOWLEDGMENTS**

The authors would like to thank Dr. Peter Squire, Office of Naval Research, Code 34, for supporting this research.

## REFERENCES

- ABC News. (2016, July 18). *Treating PTSD with virtual reality therapy: A way to heal trauma*.  
<https://abcnews.go.com/Technology/treating-ptsd-virtual-reality-therapy-heal-trauma/story?id=38742665>
- Balk, S., Bertola, M., & Inman, V. (2017). *Simulator sickness questionnaire: Twenty years later. Proceedings of the Ninth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 257–263. <https://doi.org/10.17077/drivingassessment.1498>
- Bayer, M. M., Rash, C. E., & Brindle, J. H. (2009). *Introduction to helmet-mounted displays* (Report No. 614362011-004). U.S. Army Aeromedical Research Laboratory. <https://doi.org/10.1037/e614362011-004>
- Boucsein, W. (2012). *Electrodermal activity* (2nd ed.). Springer Science + Business Media.  
<https://doi.org/10.1007/978-1-4614-1126-0>
- Caserman, P., Garcia-Agundez, A., Konrad, R., Göbel, S., & Steinmetz, R. (2021). Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality*, 25, 1153–1170. <https://doi.org/10.1007/s10055-021-00513-6>
- Champney, R. K., Stanney, K. M., Hash, P., Malone, L., Kennedy, R. S., & Compton, D. (2024). Augmented reality head-mounted display at-sea use causes cybersickness. *Applied Ergonomics*, 116, 104224.  
<https://doi.org/10.1016/j.apergo.2023.104224>
- Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual reality sickness: A review of causes and measurements. *International Journal of Human-Computer Interaction*, 36(17), 1658-1682.  
<https://doi.org/10.1080/10447318.2020.1778351>
- Chang, P. (2018, October 12). *U.S. Navy enlists virtual and augmented reality for cutting-edge training and recruitment*. *ARPost*. <https://arpost.co/2018/10/12/us-navy-virtual-augmented-reality-cutting-edge-training-recruitment/>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.
- Dennison, M. S., & D'Zmura, M. (2025). A physiological adaptation framework for cognitive load and stress in VR using HRV. <https://arxiv.org/abs/2504.06461>
- DuBois, P. O. C. C., II. (2023, August 15). *Virtual reality makes its debut in Navy training with a team approach to mental health*. *Naval Surface Force, U.S. Pacific Fleet*.  
<https://www.surfpac.navy.mil/Media/News/Article/3493950/virtual-reality-makes-its-debut-in-navy-training-with-a-team-approach-to-mental/>
- Feltham, J. (2021, November 26). *SimplePlanes VR coming to Oculus Quest and PC VR next month*. *UploadVR*.  
<https://www.uploadvr.com/simpleplans-vr-release-date/>
- Foote, B. D., & Melzer, J. (2015, April). A history of helmet-mounted displays at Rockwell Collins. In *Head- and Helmet-Mounted Displays XX* (Vol. 9470, 94700T). SPIE. <https://doi.org/10.1117/12.2177095>
- Garrido, L. E., Frías-Hiciano, M., Moreno-Jiménez, M., Cruz, G. N., García-Batista, Z. E., Guerra-Peña, K., & Medrano, L. A. (2022). Focusing on cybersickness: Pervasiveness, latent trajectories, susceptibility, and effects on the virtual reality experience. *Virtual Reality*, 26(4), 1347–1371. <https://doi.org/10.1007/s10055-022-00636-4>

- Gavgani, A. M., Nesbitt, K. V., Blackmore, K. L., & Nalivaiko, E. (2017). Profiling subjective symptoms and autonomic changes associated with cybersickness. *Autonomic Neuroscience: Basic and Clinical*, 203, 41–50. <https://doi.org/10.1016/j.autneu.2016.12.004>
- Intel. (2024). *Virtual reality vs. augmented reality vs. mixed reality*. <https://www.intel.com/content/www/us/en/tech-tips-and-tricks/virtual-reality-vs-augmented-reality.html>
- Islam, R., Lee, Y., Jaloli, M., Muhammad, I., Zhu, D., Rad, P., Huang, Y., & Quarles, J. (2020). Automatic detection and prediction of cybersickness severity using deep neural networks from users' physiological signals. In *Proceedings of the 2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 400–411). IEEE. <https://doi.org/10.1109/ISMAR50242.2020.00066>
- Johnson, D. (2020, December 4). *What is augmented reality? Here's what you need to know about the 3D technology*. *Business Insider*. <https://www.businessinsider.com/guides/tech/what-is-augmented-reality>
- Jones, M., Kennedy, R., & Stanney, K. (2004). Toward systematic control of cybersickness. *Presence: Teleoperators and Virtual Environments*, 15(5), 589–600. <https://doi.org/10.1162/1054746042545247>
- Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3(3), 203–220. [https://doi.org/10.1207/s15327108ijap0303\\_3](https://doi.org/10.1207/s15327108ijap0303_3)
- Khan, S., & Chang, R. (2013). Anatomy of the vestibular system: A review. *NeuroRehabilitation*, 32, 437–443. <https://doi.org/10.3233/NRE-130866>
- LaViola, J. J. (2000). A discussion of cybersickness in virtual environments. *SIGCHI Bulletin*, 32(1), 47–56. <https://doi.org/10.1145/333329.333344>
- Lawson, B. D., & Stanney, K. M. (2021). Editorial: Cybersickness in virtual reality and augmented reality. *Frontiers in Virtual Reality*, 2, Article 759682. <https://doi.org/10.3389/frvir.2021.759682>
- Lyndall, S. D. (2020). *The effectiveness of virtual simulation*. *Army University Press*. <https://www.armyupress.army.mil/Journals/NCO-Journal/Archives/2020/July/The-Effectiveness-of-Virtual-Simulation-as-a-Training-Tool/>
- Malyasov, D. (2020, February 21). *U.S. soldiers use virtual reality for training on weapons system to bust enemy bunkers*. *Defence Blog*. <https://defence-blog.com/u-s-soldiers-use-virtual-reality-for-training-on-weapons-system-to-bust-enemy-bunkers/>
- Meta. (2025). *Meta Quest 3: Mixed reality VR headset*. *Meta*. <https://www.meta.com/quest/quest-3/>
- Metcalfe, T. (2018, March 15). *What is VR? The devices and apps that turn the real world virtual*. *NBC News*. <https://www.nbcnews.com/mach/science/what-vr-devices-apps-turn-real-world-virtual-ncna857001>
- Muth, E. R., & Lawson, B. (2003). Using flight simulators aboard ships: Human side effects of an optimal scenario with smooth seas. *Aviation, Space, and Environmental Medicine*, 74(5), 497–505.
- Napier, J. (2024, August 6). *Revolutionizing Marine Corps maintenance with AR/VR technology*. *United States Marine Corps*. <https://www.marines.mil/News/News-Display/Article/3884413/revolutionizing-marine-corps-maintenance-with-arvr-technology/>
- National Oceanographic Data Center, U.S. Department of Commerce. (2018). *World ocean database: Code tables*. [https://www.nodc.noaa.gov/OC5/WOD/CODES/s\\_18\\_sea\\_state.html](https://www.nodc.noaa.gov/OC5/WOD/CODES/s_18_sea_state.html)

- Naval Air Systems Command. (2021, February 8). *Navy engineers developing augmented reality headsets to revolutionize maintenance and repair worldwide*. <https://www.navair.navy.mil/news/Navy-engineers-developing-augmented-reality-headsets-revolutionize-maintenance-and-repair>
- Naval Sea Systems Command. (2018, June 29). *Navy pursues augmented and virtual reality to enhance fleet readiness*. <https://www.navsea.navy.mil/Media/News/Article/1563784/navy-pursues-augmented-and-virtual-reality-to-enhance-fleet-readiness/>
- Navy APH-6 phantom VTAS visual target acquisition system helmet. (2018, November 21). *U.S. Militaria Forum*. <https://www.usmilitariaforum.com/forums/index.php?topic/319479-navy-aph-6-phantom-vtas-visual-target-acquisition-system-helmet/>
- Nguyen, D.-N., & Nguyen, D.-B. (2023). Estimation of the wave-induced roll-pitch angle of surface vessels. *Journal of Engineering Science and Technology*, 18(1), 439–449.
- Oh, H., & Son, W. (2022). Cybersickness and its severity arising from virtual reality content: A comprehensive study. *Sensors*, 22(4), 1314. <https://doi.org/10.3390/s22041314>
- OpenAI. (2025). *ChatGPT (Version 4o)* [Computer software]. <https://chatgpt.com/>
- Patterson, F., & Muth, E. (2010). *Cybersickness onset with reflexive head movements during land and shipboard head-mounted display flight simulation* (Technical Report). Naval Air Systems Command, Acquisitions Division, PMA-205.
- Perry, R. (2023, March 23). *Bringing the virtual world into reality*. United States Navy. <https://www.navy.mil/Press-Office/News-Stories/Article/3338645/bringing-the-virtual-world-into-reality/>
- Reason, J. T., & Brand, J. J. (1975). *Motion sickness*. Academic Press.
- Rebenitsch, L., & Owen, C. (2016). Motion sickness and virtual reality. *ACM Computing Surveys*, 50(4), 1–39. <https://doi.org/10.1145/2854006>
- Reyero Lobo, P., & Perez, P. (2022). Heart rate variability for non-intrusive cybersickness detection. In *Proceedings of the 2022 ACM International Conference on Interactive Media Experiences* (pp. 221–228). Association for Computing Machinery. <https://doi.org/10.1145/3505284.3529973>
- Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3(3), 195–240. [https://doi.org/10.1207/s15326969eco0303\\_2](https://doi.org/10.1207/s15326969eco0303_2)
- Rolland, J. P., & Cakmakci, O. (2005, February). The past, present, and future of head-mounted display designs. In *Head- and Helmet-Mounted Displays X* (Vol. 5638, pp. 1–12). SPIE. <https://doi.org/10.1117/12.575697>
- Rolland, J. P., & Hua, H. (2005, March). Head-mounted display systems. In B. Javidi & F. Okano (Eds.), *Three-dimensional TV, video, and display IV* (Vol. 5664, pp. 207–215). SPIE. <https://doi.org/10.1117/12.589041>
- Roza, D. (2021, August 11). *An F-35 pilot's helmet costs more than a Ferrari and takes two days to get fitted*. Task & Purpose. <https://taskandpurpose.com/tech-tactics/air-force-f-35-helmet-fitting/>
- Sanchez, M. (2016, December 2). *F-35 helmet: An advance in flight technology*. <https://www.doncio.navy.mil/chips/ArticleDetails.aspx?ID=8490>
- Seong, S., & Park, J. (2024). Tracking motion sickness in dynamic VR environments with EDA signals. *International Journal of Industrial Ergonomics*, 99, 103543. <https://doi.org/10.1016/j.ergon.2023.103543>

- Setiowati, N. O., Wijayanto, T., & Trapsilawati, F. (2020). Identifying cybersickness when wearing a head-mounted display through heart rate variability data. *IOP Conference Series: Materials Science and Engineering*, 885(1), 012069. <https://doi.org/10.1088/1757-899X/885/1/012069>
- Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5, Article 258. <https://doi.org/10.3389/fpubh.2017.00258>
- Span, M. M. (2023, November 23). *LSL - Polar H10* [Computer software]. <https://markspan.github.io/Polar/>
- Stanney, K. M., Hale, K. S., Nahmens, I., & Kennedy, R. S. (2003). What to expect from immersive virtual environment exposure: influences of gender, body mass index, and past experience. *Human factors*, 45(3), 504–520. <https://doi.org/10.1518/hfes.45.3.504.27254>
- Stanney, K. M., Kennedy, R. S., & Drexler, J. M. (1997). Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 41(2), 1138–1142. <https://doi.org/10.1177/107118139704100292>
- Tavabi, L., Poon, A., Rizzo, A., & Soleymani, M. (2020). *Computer-based PTSD assessment in VR exposure therapy*. In Q. Z. Sheng, T. Strang, & A. Mitra (Eds.), *HCI International 2020 - Late breaking papers: Virtual and augmented reality* (Lecture Notes in Computer Science, Vol. 12428, pp. 440–449). Springer. [https://doi.org/10.1007/978-3-030-59990-4\\_32](https://doi.org/10.1007/978-3-030-59990-4_32)
- Varela, J., & Soares, C. (2011). Interactive simulation of ship motions in random seas based on real wave spectra. In *Proceedings of the International Conference on Computer Graphics Theory and Applications* (pp. 235–244). <https://doi.org/10.5220/0003324502350244>
- Vestibular system, anatomy, function and vestibular system disorders*. (2019, June 4). Health Jade. <https://healthjade.net/vestibular-system/>
- Vianez, A., Marques, A., & Simões de Almeida, R. (2022). Virtual reality exposure therapy for armed forces veterans with post-traumatic stress disorder: A systematic review and focus group. *International Journal of Environmental Research and Public Health*, 19(1), Article 464. <https://doi.org/10.3390/ijerph19010464>
- Vrgal. (2024, January 13). *How VR simulation is revolutionizing military training: Exploring the possibilities*. <https://vrgal.net/vr-in-military-training/>
- Wang, J., Shen, Y., Lin, P., & Liang, L. (2024). Modeling and simulation analysis of ship 6-dof simulation swing platform based on MATLAB. *E3S Web of Conferences*, 522, 01055. <https://doi.org/10.1051/e3sconf/202452201055>
- Weech, S., Kenny, S., & Barnett-Cowan, M. (2019). Presence and cybersickness in virtual reality are negatively related: A review. *Frontiers in Psychology*, 10, 158. <https://doi.org/10.3389/fpsyg.2019.00158>