A Virtual Reality Simulator for Enhancing Marine Pollution Control Efforts

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Abstract. We developed and assessed the Marine Pollution Control Simulator VR, a virtual reality training platform designed to improve the preparedness of marine pollution control teams. Traditional training for marine oil spills is costly and poses logistical and safety challenges. Our VR-based solution offers an immersive environment for training in oil spill containment and recovery, featuring navigation and equipment manipulation. The project emphasizes collaborative emergency response simulations, particularly vessel coordination. A user study evaluated the simulator's usability, immersion, and potential for simulator sickness. Participants found the VR environment immersive and beneficial for training, though usability and physical discomfort issues were noted. These findings highlight the need for further refinements to enhance user experience and reduce adverse effects.

Keywords: Virtual Reality · Training · Marine Pollution Response

1 Introduction

Simulators are invaluable tools for training in high-risk professions like ship navigation [2], aviation [4], and healthcare [3]. They provide a safe environment for practice without risking lives or expensive equipment, allowing users to learn from mistakes and prepare for rare scenarios, such as evacuating a sinking ship.

To bring these benefits to marine pollution control, the Marine Pollution Control Simulator (MPCS) project developed a desktop and cloud-based platform for training and evaluation. This simulator creates virtual scenarios for spill containment, enabling users to assume various roles in a multi-user environment and interact with equipment and each other to achieve training goals. However, the desktop platform has limitations in training for operational handling of equipment.

To address this, we developed a VR-based simulation module for cooperative maritime operations, such as deploying oil containment barriers and suction pumps. Leveraging VR technology, MPCS-VR offers an immersive environment that mitigates the high costs, logistical challenges, and safety risks of traditional training. The VR simulator has potential to enhance traditional methods by providing realistic scenarios for practicing oil spill containment and recovery.

This paper details the development of the VR module, including design considerations and implementation of features like player movement and object manipulation. A user study validated the simulator's effectiveness, highlighting its usability and immersive experience, while identifying areas for improvement. This work demonstrates the potential of VR technology to enhance preparedness and efficiency in marine pollution control.

2 Interaction Scenario

In marine pollution control, the primary goal is to contain and clean up oil spills to minimize environmental damage. Oil and hydrocarbons (HCs), being less dense than water, float on the ocean surface and can spread quickly without containment measures [18]. This process involves coordinated efforts among multiple teams and specialized equipment.

Upon detecting an HC spill, a rapid, coordinated response is essential. An alarm is raised, mobilizing response teams. The Incident Commander and environmental experts develop a strategy based on the spill's characteristics and conditions. This typically involves deploying containment booms to prevent further spread and using skimmers to recover the oil. The strategy considers various factors, including the HC type, spill extent, and weather conditions. The "J" configuration, involving two vessels, is often used: one with the containment boom and another with the skimmer.

Equipped vessels navigate to the spill site using GPS coordinates. Deployment begins with the vessel carrying the boom barrier. A crew member launches one end of the boom, and the second vessel secures the other end, creating a boundary around the spill. Both vessels work together to form a "J" shaped barrier, concentrating the oil towards a collection point. Teams continuously monitor and adjust the setup to maintain an effective containment perimeter against environmental forces.

With the oil contained, the recovery process begins. The vessel with the skimmer moves into position, and a crew member lowers the skimmer head into the oil. The skimmer pumps the oil into onboard containers, requiring careful handling to maximize recovery and minimize water intake. Once the oil is collected, the crew retrieves the skimmer and secures the boom. Both vessels then return to port, where the collected oil is transferred for safe disposal or recycling.

This scenario outlines the critical phases of equipment deployment and oil recovery in marine pollution control operations, which are simulated in the VR training platform.

3 Related Work

The integration of VR in maritime operations training is a recent approach to enhance maritime education and safety. Research shows VR's significant benefits across various maritime applications, from design to safety training.

Aylward et al. [1] illustrate VR's use in design processes, showing its potential for comprehensive and immersive evaluations in maritime settings. This demonstrates VR's utility not only as a training tool but also in design and planning, giving designers a deeper understanding of maritime environments and challenges. Buenaobra et al. [6] and Voloshynov et al. [16] study VR's impact on maritime education and training, finding it significantly boosts learning outcomes, engagement, and motivation compared to traditional methods. Markopoulos & Luimula [11] validate VR-based training's effectiveness in maritime safety, highlighting the benefits of immersive technologies for simulating critical safety procedures and operations.

Markopoulos et al. [12] focus on finger tracking and hand recognition technologies for maritime safety training. Their work emphasizes the importance of precise interaction within VR simulations for effective training, especially in complex operations requiring fine motor skills. Shen et al. [15] enhance realism in VR applications with real-time dynamic simulation of 3D clouds, essential for preparing personnel for hazardous conditions and improving decision-making and situational awareness.

Beyond training and education, Secci et al. [14] demonstrate VR's potential for virtual diving experiences on historic shipwrecks, while Correia et al. [7] and Makransky & Klingenberg [10] explore its use in maritime rescue training and safety training effectiveness.

Despite extensive research, VR applications in pollution control training, particularly for operating vessels and equipment like barriers and skimmers, are lacking. Our work focuses on marine pollution control, emphasizing coordinated activities to reach, contain, and collect hydrocarbons.

4 MPCS VR

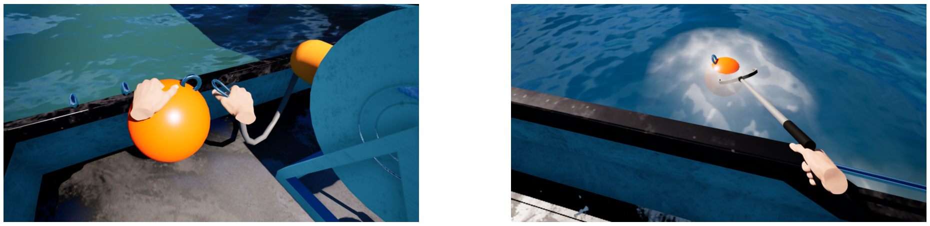
The MPCS VR component of the MPCS project provides a multiplayer VR experience for practicing coordinated marine pollution control operations. Users can place oil spill containment barriers and pilot boats, carrying equipment and operators, to contain and divert contamination to a collection point. The prototype, developed with Unreal Engine 5, was tested on Meta Quest 2.

The VR module includes various functionalities that were designed to simulate real-world activities and challenges with a focus on required steps, coordination and equipment manipulations.

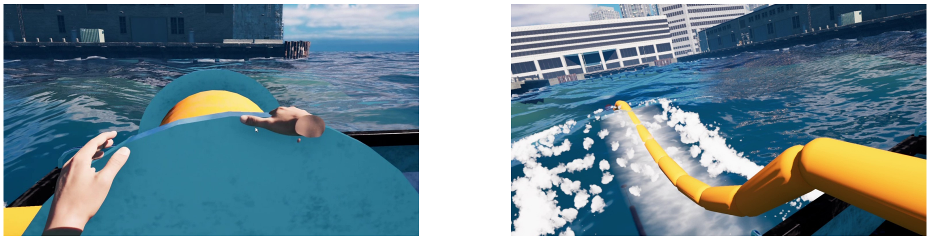
Each participant is represented by an avatar that moves through the scenario via teleportation or natural walking. Using the right-hand joystick, users control the teleport mechanism: pushing the joystick generates a teleport pointer, and releasing it teleports the user (Fig. 1a).

(a) Teleport mechanism. (b) Pointer interaction with GUI.

(c) Hand on the steering wheel. (d) Hand on the throttle handle.



(e) Connecting a buoy to the barrier. (f) Catching objects with a claw.



(g) User rotating the reel's wheel. (h) Barrier being deployed.

(i) Pressing start button on the pump. (j) GPS shows the location of the spill.

Fig. 1: Interactions and functionalities.

Interactions with menus and other 2D interfaces are mediated through a ray-shaped pointer that is projected from the avatar's right hand (Fig. 1b). By pressing the trigger button on the right controller, users are able to perform an equivalent to a left click on a mouse.

Each avatar has virtual hands matching the controllers' position relative to the VR headset (Figs 1c and 1d). By pressing buttons, users can perform different hand gestures: A/X or B/Y buttons close the thumb; the trigger button closes the index finger; the grip button closes the other fingers. These standard poses are mapped to various manual interactions.

All the interactions between the users and the virtual world are mediated by the avatars' hands by performing the grip gestures. Users are able to grab different pieces of equipment, which can then be pushed, pulled, rotated, or freely moved, depending on the constraints that they have. Through them, users can:
Drive the boat by grabbing and rotate the steering wheel inside the boat's cockpit in order to adjust its direction and grabbing and push/pulling the throttle handle to control the engine power (Figs 1c and 1d).
Connect and disconnect objects with/from cables (Fig. 1e). To connect the cable to an object, users must grab the carabiner located at the cable's end and release it close to the object's attachment point (metal ring). To disconnect the two objects, users grab the carabiner and move it away from the attachment point.
Catch objects with a claw by grabbing it and opening or closing it by pressing the trigger button (Fig. 1f).
Deploy the barrier by grabbing and rotating the reel's wheel, users are able to unroll the barrier and release it into the ocean (Fig. 1g).
Collect the HC on vessels equipped with a suction skimmer. To do so, users grab the skimmer's head and put it into the water, close to the oil spill, and then press the button on the pump to start recovering the HC (Fig. 1i).

Inside each vessel, users have access to a GPS monitor that they can use to orient themselves within the virtual training environment (Fig. 1i). Through that monitor, users can check their location in the world, represented by a green arrow, as well as the current position of the oil spill, represented by a red circle.

Throughout the VR experience, users receive several messages indicating the next task that must be performed. Each message received is notified to users by a vibration in the left control. Pressing the X button opens a floating window near the left hand, through which users can read the notification.

Players can practice frequent actions in a tutorial area before entering the main training area. In the tutorial area users can learn how to move through teleport, how to rotate the view, how to grab and drop objects, how to use tools to grab and drop objects, how to attach objects, and how to unwind the reel.

The MPCS VR module uses Unreal Engine 5's tools and libraries to establish a client-server model. Each player connects to a server hosting VR game sessions. The server replicates game state information to clients, including object positions, player locations, behaviors, and variable values. Clients then simulate the server's state, providing a close approximation of the actual game. While play-

Table 1: Evaluation tasks.

Task	Description
T1	Drive the boat to the contaminated area
T2	Use a cable to connect the barrier's end to a buoy and throw it into the water
T3	Unroll the barrier into the water
T4	Contain the oil spill (by encircling it)
T5	Use a claw to catch the buoy and attach the cable to the boat
T6	Use the skimmer to collect the oil

ers view the game through the client, the server manages the coordinated game state.

5 User Study Evaluation

After developing an initial version of the VR module, we proceeded with a series of tests in order to find potential problems and design opportunities with the implemented mechanics, and assess the system's usability, sense of presence, and symptoms developed in the users.

5.1 Test Procedure

We recruited participants from our department through direct contact. Each test began with a brief introduction to the simulator, explaining the MPCS VR project goals and the evaluation's purpose. Participants then filled out a demographic form and signed an informed consent. They completed a tutorial to learn how to interact with the simulator before performing the tasks listed in Table 1.

The initial training scenario was designed for two individuals but, due to material limitations, tests were conducted individually. The training session was divided into two parts: in the first, participants connected to the server and performed tasks aboard the vessel with the barrier. In the second part, they reconnected with a new player ID to perform tasks aboard the second vessel. After the training, participants completed questionnaires to provide feedback on their experience.

Through direct observation, the following behaviours were identified and categorised as operation errors: trying to grab an object with the hand but failing; trying to grab an object with the claw but failing; accidentally dropping an object; poorly positioning the boat and having to readjust it.

At the end of the tests, we used 3 standard questionnaires, implemented in Google Forms: SUS (System Usability Scale) [5], PQ (Presence Questionnaire) by Witmer and Singer [17], and SSQ (Simulator Sickness Questionnaire) [9] to gather feedback about the system's usability, presence, and cybersickness developed in the users. For PQ, we used the structured provided by [13]. This questionnaire consists of 24 questions presented in the form of likert scales with

Table 2: Task performance measurements.

Task	**Error Rate**		**Completion Time (s)**	
	Avg.	**Std. Dev.**	**Avg.**	**Std. Dev.**
T1	1.75	1.82	107.77	18.97
T2	2.08	1.78	34.48	17.53
T3	1.25	1.14	25.02	4.89
T4	1.50	1.45	86.10	49.70
T5	6.33	2.64	153.69	40.05
T6	0.67	0.98	27.64	7.60

7 levels and three anchors ("not at all", "somewhat", "completely"), organized around 7 subscales (Table 3) that represent factors that contribute to the sense of presence. the SSQ was filled out twice by participants (before and after using the simulator). The SSQ consists a series of questions in which participants evaluate the intensity of different symptoms. Each question is rated on a 4-option scale with numeric values associated("None": 0, "Slight": 1, "Moderate": 2, and "Severe": 3), each of which has a specific value associated. The questionnaire is composed of three factors, each composed of 7 items of the questionnaire (with some overlap): Nausea (items 1, 6, 7, 8, 9, 15, 16), Oculomotor Problems (items 1, 2, 3, 4, 5, 9, 11), and Disorientation (items 5, 8, 10, 11, 12, 13, 14).

5.2 Results

The evaluation group consisted of 12 participants. Demographics showed 67% were aged 18-24, with three below 18 and one above 34. The group was predominantly male (66.7% vs with 33.3% female). Experience with virtual reality was balanced: 58.3% had never used VR, while 41.7% had prior experience, all for entertainment. These experienced participants had less than one hour of VR exposure in the previous week, playing various game genres. These participants reported playing Action, Adventure, Horror, Rhythm, Simulation, and Sports games in VR.

Despite being a young group with limited VR experience and no domain familiarity, this sample is considered representative for an initial study aimed at training or raising awareness among citizen volunteers.

Task performance and usability During the tests, we recorded metrics such as error rates and completion times to measure participants' performance on the tasks listed in Table 1. Table 2 shows the average error rates and completion times. Task 5 – using a claw to catch a buoy and attach a cable to the boat – had notably higher error rates and completion times. Participants struggled to position the boat correctly and had visibility issues due to the boat's sidewalls, which required them to frequently leave and re-enter the cockpit. These

Table 3: Results for the Presence Questionnaire by subscale.

Subscale (items)	**Average**	**Std deviation**
Realism (3, 4, 5, 6, 7, 10, and 13)	1.76	0.91
Possibility to Act (1, 2, 8, and 9)	1.96	0.57
Interface Quality (14, 17, and 18)	1.94	1.14
Possibility to Examine (11, 12, and 19)	2.08	0.79
Self-Assessment of Performance (15 and 16)	1.54	1.08
Sounds (20, 21, and 22)	0.83	1.46
Haptic Effects (23 and 24)	1.04	1.12

difficulties could indicate real-world challenges, simulator operation issues, or insufficient experience.

Other tasks had fewer issues, though some participants struggled with the boat's steering wheel during tasks 1 and 6 due to its symmetry, making it difficult to determine how much it was rotated. Additionally, frequent errors occurred when trying to grab objects on the ground, suggesting the need to extend interaction distance thresholds.

SUS scores ranged from 62.5 to 95, with an overall median of 76.3 and an average of 79.0, indicating acceptable to good usability. According to Sauro's analysis, an average score of 79 places the MPCS VR system near the 85th percentile, ranking it better than 85% of systems analyzed.

Presence When analysing the results from the PQ, we normalized the data to a zero-centred scale [-3, 3]. Results are shown in Table 3 and Figure 2 (a full results table is provided as supplementary material).

The Realism subscale indicates a moderate level of immersion (average score of 1.76), with visual aspects and the sense of movement within the VE being somewhat compelling. However, there's a noticeable variance in responses, especially in how natural the control mechanisms felt, suggesting inconsistency in user experience. The item that received the lowest average answer was item 5. This may have been due to the fact that participants had a small physical area to naturally walk and were mostly forced to use the teleport function to move around.

The Possibility to Act subscale suggests participants felt they had a moderate ability to control events and that the environment was somewhat responsive (average score of 1.96). However, there is still room for improvement in making actions within the VE more responsive or predictable.

In the Quality of Interface subscale (average score of 1.94), participants noted some delay between actions and outcomes, but answers to items 17 and 18 were highly positive indicating that the visual interfaces and interaction mechanisms were appropriate. We were running the simulation by streaming from a PC to the headset, wirelessly, which may have affected the experience. These factors can significantly impact the sense of presence and should be areas of focus for enhancement.

The Possibility to Examine scored slightly higher (average score of 2.08), indicating participants found examining objects from multiple viewpoints relatively effective. This suggests that the visual aspects of the VE were engaging and provided a sense of depth and exploration. Still, perhaps due to the novelty of the experience, participants felt less confident regarding item 19, which relates to being able to concentrate on the task rather than on the interaction mechanisms.

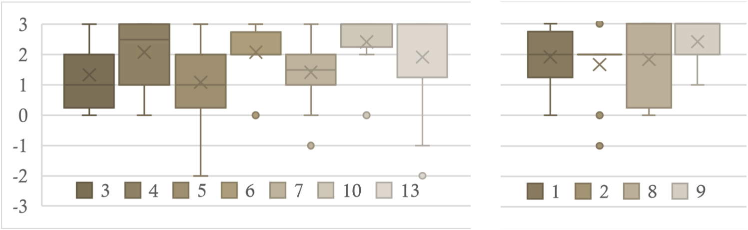
Scores for the Self-evaluation of Performance (average score of 1.54) suggest participants did not feel overly proficient in navigating or interacting with the VE. This could reflect a learning curve or indicate the need for more intuitive or user-friendly interface designs. It should be noted that participants did not have experience in maneuvering real boats, which may have also impacted the scores for this subscale given that it is a task that requires practice.

The Sounds and Haptics subscales scored notably low (averages of 0.83 and 1.04) highlighting a significant areas for improvement. Enhancing auditory aspects of the VE can greatly augment the realism and immersion, which seems lacking in the current implementation (currently there is only the sound of the boat's engine, and the sound of waves. The low scores suggest that haptic feedback was either ineffective or detracted from the experience, particularly in terms of exploring the environment through touch. However, it should be noted that haptics were limited to controller vibrations when manoeuvring the boat (rotating the steering wheel or adjusting the throttle), or when alerting the player to a new task.

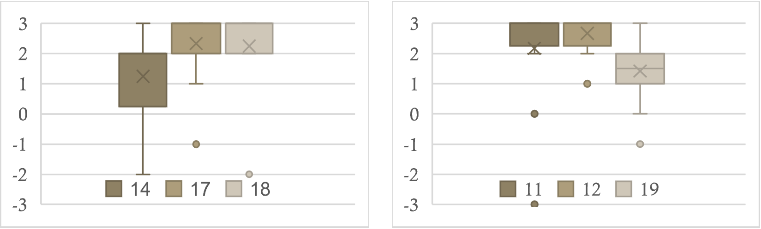
Simulator Sickness For the SSQ, we calculated the scores for each factor as well as a total score, based on [9].

In assessing the normality of the distributions for the simulator sickness questionnaire scores, the Shapiro-Wilk test was conducted for each subscale. The test indicated that the scores for nausea ($W = 0.73$, $p < .01$), oculomotor ($W = 0.56$, $p < .001$), disorientation ($W = 0.33$, $p < .001$), and total score ($W = 0.65$, $p < .001$) before the intervention significantly deviated from a normal distribution. Similarly, after the intervention, the scores for disorientation ($W = 0.77$, $p < .01$) and total score ($W = 0.82$, $p = .016$) also deviated from normality, while nausea ($W = 0.91$, $p = .214$) and oculomotor ($W = 0.86$, $p = .044$) subscale scores did not exhibit a significant departure from normality.

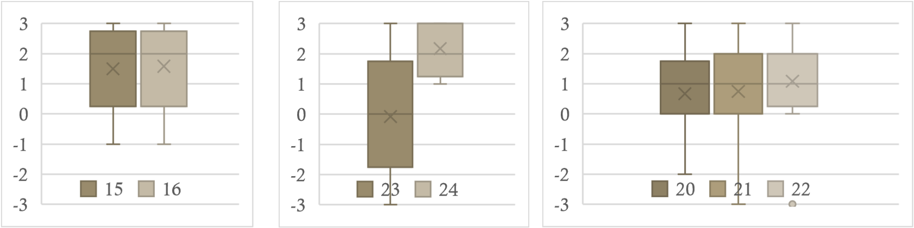
To evaluate the changes in simulator sickness scores before and after the MPCR VR experience, the Wilcoxon Signed-Rank Test was applied due to the non-normal distribution of the data. The test revealed statistically significant differences in the median scores for nausea ($T = 2$, $p = .0089$), oculomotor ($T = 2.5$, $p = .0334$), disorientation ($T = 2$, $p = .0498$), and total score ($T = 3$, $p = .0052$). These results suggest that the VR experience had a significant impact on participants' perceived levels of simulator sickness across all measured dimensions.



(a) Realism (b) Possibility to act

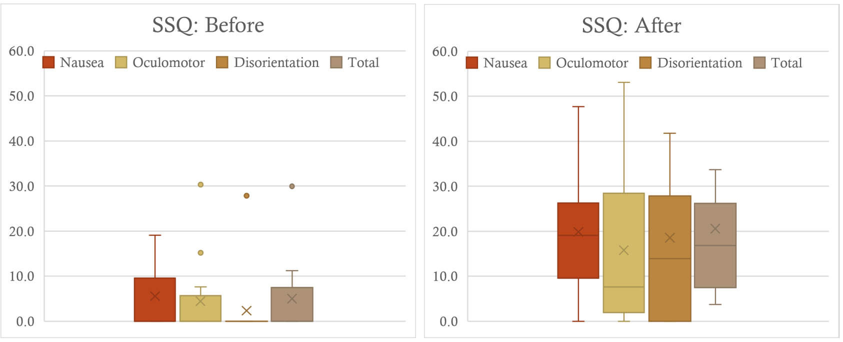


(c) Quality of interface (d) Possibility to examine



(e) Self evaluation of perf. (f) Haptics (g) Sounds

Fig. 2: Boxplots for the results of the Presence Questionnaire, organized by subscale.



(a) Before (b) After

Fig. 3: Boxplots for the results of the SSQ questionnaire.

Table 4: Individual scores for the SSQ (after) questionnaire.

	Nausea	Oculomotor	Disorientation	Total
	19.1	0.0	0.0	7.5
	38.2	22.7	27.8	33.7
	19.1	7.6	0.0	11.2
	19.1	30.3	13.9	26.2
	0.0	7.6	13.9	7.5
	9.5	22.7	41.8	26.2
	47.7	53.1	83.5	67.3
	9.5	0.0	0.0	3.7
	28.6	7.6	27.8	22.4
	9.5	0.0	0.0	3.7
	19.1	7.6	0.0	11.2
	19.1	30.3	13.9	26.2
Average	19.9	15.8	18.6	20.6
StDev	13.2	16.3	24.7	17.9
Median	19.1	7.6	13.9	16.8

According to [8], scores between 10 and 15 indicate significant symptoms, between 15 and 20 indicate concerning symptoms, and above 20 indicate that the simulator is problematic. This categorization was established based on normative data obtained from the evaluations of computer flight simulators conducted by the Army and Navy of the United States. However, it is important to note that SSQ scores are always higher in virtual environments, moving to an average score of 15 points, instead of 5 [8].

Results for the SSQ (after) questionnaire (Table 4) show that all three factors' averages are above 15 and the total score average is above 20. Further looking into the total score, we see that half of the participants reported a total score of 11.22 or less and half reported a total score of 22.44 or higher, i.e., half of the participants experienced a problematic level of sickness. This seems to indicate that sickness is an aspect that needs further investigation as to what may be causing it.

It is important to mention that the tests were conducted in non-air-conditioned spaces and at a time of the year when temperatures reach their peak, so the conditions were not the most favorable for carrying out some of the evaluations. A consequence of this is the high reported values for item 7 associated with sweating – several participants complained about the sweat in their faces due to the headset. This however, only accounts for the high nausea factor. Further investigation would be required to understand the causes of the other symptoms.

A final aspect it that the MPCS VR puts players in a situation that is naturally prone to causing sickness (e.g., sea sickness) in the real world. Even though we purposefully restricted the boat's movement so that it would not be influenced by the waves, the optical wave movement might still represent a possible cybersickness cause. Further work is needed to assess how to reduce cybersickness in sea related VR experiences.

6 Conclusions

Oil spills are devastating environmental disasters with immediate and long-term impacts on marine ecosystems and regional economies. Rapid and effective response is crucial to minimize damage and aid recovery. Regular training is essential for marine pollution response teams to maintain high performance and coordination. The MPCS platform uses simulation to provide a safe, controlled environment for enhancing oil spill response skills.

This study developed and evaluated a VR-based training module to improve marine pollution control preparedness and efficiency. The MPCS VR simulator leverages immersive technology for environmental disaster response training, particularly in marine pollution control. VR simulations offer a safe, cost-effective, and immersive learning environment for practicing complex and hazardous scenarios.

User feedback highlighted the simulator's usability and immersion but also pointed out areas for improvement. Some participants experienced simulator sickness, emphasizing the need for further optimization.

Future work will refine the VR simulator's design, explore advanced interaction techniques, and expand scenarios for comprehensive training. Integrating adaptive learning algorithms could tailor training to individual skill levels. Studying cybersickness is also critical, especially if motion simulators are added to the module.

In conclusion, the MPCS VR project demonstrates the potential of VR for training and education in environmental protection and disaster response. Continued innovation and refinement will better prepare marine pollution control teams to respond effectively to environmental emergencies, safeguarding marine ecosystems for future generations.

6.1 Limitations

We acknowledge several limitations in our work that offer avenues for future research:

Sample Size and Diversity: The user study had a limited number of participants, restricting the generalizability of findings. Additionally, the diversity in participants' VR experience and marine pollution control knowledge was not extensively detailed. Future studies should include a broader and more varied cohort for more representative results.

Simulator Sickness: Simulator sickness was noted but not explored in depth. Further investigation is needed to understand its causes, prevalence, and mitigation strategies to improve user experience.

Comparison with Traditional Training Methods: This study did not compare VR training directly with traditional methods. Such analysis could highlight the advantages or potential shortcomings of VR training and provide empirical support for its adoption as a complement to traditional training.

Long-Term Impact: The research focused on immediate usability and user experience without examining long-term impacts like skill retention, transferability to real-world scenarios, and training efficacy over time. Longitudinal studies are needed to assess the sustained benefits and effectiveness of VR-based training.

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