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Comparing a VR Ship Simulator Using an HMD With a Commercial Ship Handling Simulator in a CAVE Setup

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Abstract

The education of seafarers is extended by on-board experience and simulator training in order to prepare them for their work. Simulator training is especially helpful to acquire situation awareness and practice high risk maneuvers, which could not be performed during real missions. Unfortunately, commercial ship handling simulators are very expensive, occupy a lot of space and students are only provided with limited access and practice time. Therefore, we developed a low-cost, low-space alternative prototype using head-mounted displays (HMD). We aimed to resemble the commercial simulator, which is a cave automatic virtual environment (CAVE), as close as possible, by using real ship maneuvering data and recreating the bridge interior. Interactions with the interior were translated to controller interactions and an elementary physics simulation was added. We conducted a within-subject user study to compare our new HMD setup with an existing commercial CAVE setup. The results show, that the simulator using an HMD cannot compete with the CAVE setup in terms of realism. Although the immersion is higher, the HMD setup lacks in realism due to the low-level physics simulation. Nevertheless, the prototype is found to be a good foundation for further development as tool for educating ongoing nautical officers.

Keywords: Virtual Reality; Ship Handling Simulator; Maritime Education; Within Subject User Study;

1. Introduction

Nowadays, maritime traffic is still a central factor in the modern global economy (Manuel, 2017; de Souza and Weller, 2003). More than 90 percent of the world's trade is transported over sea (Bloor et al., 2014). Recently, the number of crew members on-board has been decreasing, in return the workload for individuals is increasing, when dealing with the ship operations. With many maritime accidents caused by human failures (Emad and Oxford, 2008), increasing speed and size of ships and constantly growing ship traffic worldwide, special attention is put on the education of maritime officers (Demirel and Mehta, 2009). In order to get qualified and competent personnel, enough practice in beforehand is important (Xiuwen et al., 2009a). A lot of experience and on-board training must be gained before getting the license as a nautical officer (Int, 2017); especially, since going to sea as a profession is recognized as dangerous (Demirel and Mehta, 2009) with high risks (Xiuwen et al., 2009b). The training and required knowledge for every seafaring candidate on ships of 500+ gross tonnage is standardized by the International Maritime Organization (IMO) via the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention) (Int, 2017).
Practicing ship maneuvers on-board is expensive (Sandurawan et al., 2011; Xiuwen et al., 2009a) and does not totally reflect the circumstances of a danger situa-

Figure 1. The different ship handling simulators (left) typically used commercial CAVE, (right) our virtual ship of the HMD setup.

tion as it would be too dangerous to expose trainees to potentially life threatening situations. A simulator is safe (Xiuwen et al., 2009a; Abasolo et al., 2014; Longo et al., 2015), flexible, has lower costs and comes with an easier possibility to repeat the training (Xiuwen et al., 2009b). Therefore, training in a simulator in beforehand is a valuable method of education and training unit (Int, 2017; Demirel and Mehta, 2009). Still, simulators are expensive and have high operating (Ghosh and Bowles, 2013) and maintenance (Sampson, 2004) costs, as the current simulators are Cave Automatic Virtual Environment (CAVE) setups, with several computers for calculations, several projectors, a standardized copy of sophisticated bridge equipment as input device, which require a lot of space (Abasolo et al., 2014).
VR technologies offer a simulated environment that feels close to the real world. Furthermore, conditions can be controlled, which makes it an effective training tool that also offers repetition. VR is immersive, because it offers a specific sense of self-location in the virtual environment (VE) and the possibility to interact with objects with a form of feedback. With the development of head-mounted displays (HMD) users can now freely move around the VE, while their position and gestures are tracked. Further benefits of VR are the stimulation of all human senses, especially the sense of vision in natural ways and new and different modalities of interaction between human and computer (Psotka, 1995).
In this paper we contribute a full mission ship bridge VR simulator using an HMD (Figure 1) to give students the possibility to gain more experience with the simulator while having lower operating costs, more flexibility and less space requirements. We conducted a user study on the usability for educational purposes of this simulator.

2. State of the art

The benefits of VR technologies can be applied in many different areas. In general, simulations can be used for distance learning or in science, as external influences, such as weather or traffic, can be controlled and dangerous situations, like accidents, can be explored without the real world consequences. Additionally, VR environments can be shared to easily recreate experiments (Psotka, 1995; Ponder et al., 2003). In general, VR technologies appear to be a promising tool for learning with completely new fields of application (i.e. danger situation) (Ponder et al., 2003; van Wyk and de Villiers, 2009). As a result, VR is currently being used and investigated for training solutions in a variety of industries and fields like military, medical sector and aircraft (van Wyk and de Villiers, 2009). Maritime simulation also plays a role and in the following, we describe its current state of the art.
In the main, maritime simulations can be used for several purposes, from studying ship behavior to training ship crews. Maritime simulation can be subdivided into two types: interactive and non-interactive simulation. Non-interactive simulations are used for studying different conditions and scenarios with an autopilot steering the vessel on a predefined route, whereas interactive models can be steered by oneself. Examples for virtual reality based simulators are manned models, remote controlled models, radar simulators, full-mission bridge simulators and virtual reality based simulators (Hensen, 1999). There are a lot more types of simulators available, such as engine room, anchor handling or crane and winch simulators (Kumar et al., 2016).
For the purpose of our research, the full-mission bridge simulators are of most relevance. They are the most advanced maneuvering devices due to their full-scale mock-up of a ship's bridge, including all instruments required for navigation and maneuvering. Additionally an out-of-window view with full-scale display of the ship and its surroundings is produced to get a high level of immersion (Hensen, 1999; Xiuwen et al., 2009a). The simulators are useful for training in intense sessions, can be connected with engine room simulators (Hreniuc and Batrinca, 2014) and allow standardized training procedures, with the possibility of repeating standard and non-standard maneuvers (Ghosh and Bowles, 2013). The high immersion of bridge simulators improves the students ability to deploy the learned skills to a real ship (Longo et al., 2015; Xiuwen et al., 2009a). Current VR SHS are realized in CAVE setups with projectors or screens displaying the 3D environment outside the ship bridge and a haptic bridge setup with the necessary equipment such as handles, radar or ECDIS (Abasolo et al., 2014; Longo et al., 2015; Sandurawan et al., 2011; Xiufeng et al., 2004; Xiuwen et al., 2009a). Besides CAVEs, there are VR setups using HMDs (Hensen, 1999; Denker et al., 2015). Denker et. al. (Denker et al., 2015) developed a simulator by using a VR-headset. In there, a virtual replica of a ship bridge was represented, including the consoles and user interfaces. For the

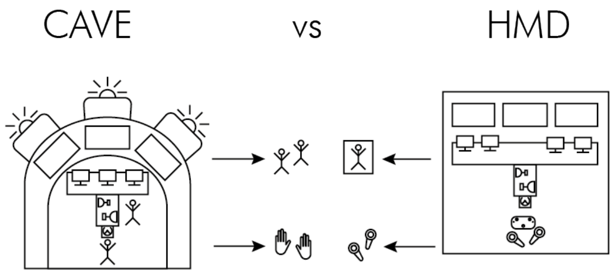

Figure 2. The concept for the HMD setup compared to the CAVE setup.

Figure 3. The study setup for both, the CAVE (left) and the HMD condition (right).

interaction, a game controller was used. With it, the user is able to control the movement and interactions of an avatar. Morlid Interaktiv (Mor, 2020) built a VR ship bridge simulator using an HMD. They developed a mobile and low cost setup with a multi-user setup and an own interaction engine based on real hand interactions. The benefits of such setups are supposed to reduce costs (Hensen, 1999; Denker et al., 2015), reliability, the possibility to simulate almost everything, and to collect neutral data without the possible influence of a present research conductor (Denker et al., 2015). However, HMD setups have limitations due to restricted interactions with the physical equipment and collaboration difficulties in multi-user setup (Hensen, 1999).

3. Materials and Methods

In order to compare a VR ship handling simulator using an HMD with a CAVE setup and determine its usability for educational purposes, the CAVE setup served as model for the HMD setup (Figure 3). The commercial simulator consists of a wooden chassis of a bridge with projectors providing the view out of the windows. The bridge is placed on the actual bridge position in the 3D models of real ships and utilizes a physical, standardized set of equipment as input devices. The information and hydrodynamics is processed in a small server room. In a training session, maneuvers are usually carried out in two-man maneuvers and controlled by an instructor in a room outside.
Since the HMD setup was realised with an HTC Vive and its controllers, interaction modalities are altered in our VR simulator. Thus, the interaction is a key difference of the simulators. In the CAVE, the users can directly interact with the equipment and get feedback, whereas with an HMD such a direct interaction is not possible. Our simulator used an HTC Vive to visualize the environment and its controllers to translate the hand interactions for the user input. A ship model and terrain database from the CAVE setup was used and built in to our simulator, whereas the virtual bridge in our setup was built into the 3D model of the ship using the original windows. This concept is shown in Figure 2. Additionally, the possibility to use the bridge wings was added, which gave the ability to steer the ship form outside the bridge. Original turning maneuvers data from the equivalent real ship was used to implement the hydrodynamics in our setup. However, due to several unknown factors in real ship movements, we lowered the fidelity in the hydrodynamics and ignored the environmental influences, such as wind and water forces. We used Unity to build our simulator and used the SteamVR Add-On for the realization in VR. For the interaction, we attached the Circular Drive script from the Add-On to all bridge instruments, which made them intractable to the controller.

3.1. User Study

Before the study, we assumed that the HMD setup will be well received by the participants. The interaction is assumed to be in need of getting used to it and unusual due to the different haptic feedback compared to real world interactions. These assumptions were based on feedback of experts. The experts tested our setup as soon, as all interactions were implemented, but the training scenario was not developed yet.

3.1.1. Study Design

A within-subject-design was chosen to receive participant's feedback directly comparing both conditions. For this reason, all participants had to perform each task under the same conditions in both setups (Butz and Krüger, 2014). The setups (Figure 3) are the dependent variable in this study and are give the possibility to fulfill a task (in this case, a learning objective for students).
The independent variables in this study are of quantitative and qualitative nature. The quantitative data consists of the estimation of the distance, the task load (measured by the NASA-TLX (Xiao et al., 2005)) and the task completion time.
For getting qualitative data, notes during the study were taken with focus on the interaction, the performance, and the general behavior of the participants. In Addition, a semi-structured interview after the whole experiment was held. Here, the main aspects were comparing both simulators by the factors: realism/immersion, situation awareness and preference. In order to elevate the situation awareness the model (Figure 4) by Øvergård et al. (Øvergård et al., 2015) was

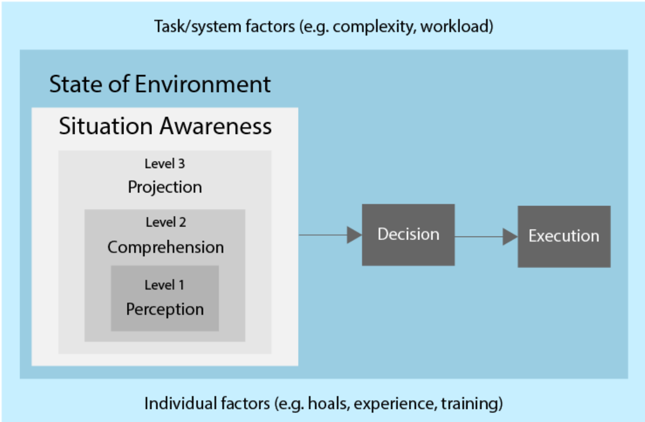

Figure 4. Situation awareness model after Endsley by Øvergård et al. (Øvergård et al., 2015)

used. The first level includes perception of elements in the current situation, the second one comprehension and the third projection into the future. All levels together are required to make decisions. For nautical students this means, they first have to be aware of their own ship, the velocity, course etc. Then they need awareness of the immediate surroundings, like buoys, harbors or other ships. Lastly, students have to project into the future, and consider the weather, the harbor and berthing tasks and make decisions accordingly.

3.1.2. Training Scenario

To test the HMD setup, a scenario where the participants must fully interact with the maneuvering aids on the ship bridge is important. Therefore, a scenario was created with the help of a supervisor working as a teacher at a nautical university. The scenario included aspects that are trained in the CAVE setup ranging from beginners, with no ship handling experience, to students with a lot of experience. Testing all ship instruments, including the bridge wings, and exercising a reasonable/real-life situation are the criteria for the scenario. In the following, the tasks for the scenario are listed:

- Following the waterway to a predefined harbor entry
- Berthing of the ship at the quay
- While berthing, a distress message comes in (maneuvering unable boat is in distress)
- Turning the own ship and gaining speed
- Leaving the harbor
- Searching the distress boat

The scenario ends when the boat is found. The optimal route is around 2.5 nautical miles (4.63 km) long and the travel time is around 15 minutes with an average speed of 12 kn (22.224 km/h). To avoid a learning effect by the participants, the route changed in its location, but not in its overall travelled distance after every condition. The task is chosen, because harbor entries/exits are very complex navigational tasks and have a high risk of collision (Hreniuc and Batrinca, 2014; Longo et al., 2015) and without training them, students are not able to gain the certificate of competence (Ghosh and Bowles, 2013). It is particularly important to train berths at simulators, because few cadets train them on-board (Sampson, 2004).

3.1.3. Participants

For the study, one instructor from a nautical university and four nautical science students from the same university were recruited, all of them in higher semesters (7 and 9). The participants were between 22 and 26 years old (Mean = 24.5, SD = 1.5), while three of them were male and one female. Two of them stated they had half a year of ship experience, one had one year of ship experience and one had more than one year of ship experience. All of them had a SHS experience of only a few times per year. Three of the participants said, they had no VR experience and one minor experiences. All students were asked to perform the scenario in the CAVE and in the HMD setup, while the supervisor was observing their behavior.

3.1.4. Procedure

In a real typical training situation, students and supervisors have a briefing about the upcoming session. Afterwards, the students perform their training, while the supervisors observe them. In the end, there is a debriefing (Int, 2002). In our study, this procedure was complied. In the beginning, the participants had a short explanation of the study, its purpose and their rights during the study. Afterwards they were asked to sign the consent and fill in a demographic questionnaire. Then, the participants were briefed by the instructor into the scenario, with showing the map and a Pilot Card, containing ship information. After the briefing, the participants were asked to perform the scenario either first in the CAVE or in the HMD setup to avoid a consistency of the performance (Butz and Krüger, 2014). Table 1 shows the counterbalance.
In the beginning of the HMD condition, there was a short settling-in period to give the participants the possibility to accustom to the HMD setup and learn the interactions. After the participants got familiar, the training scenario started. Both scenarios started with a distance estimation to another ship, which was located around 440 m away. Following this, the participants were free to fulfill their task on their own accord. After being close to the berth of the own ship, the participants received a distress message by the instructor which they also were supposed to fulfill freely. During the scenario, the instructor gave advice about maneuvers and verbally helped the participants with their task. After the scenario was completed, the participants were asked to fill out the NASA-TLX questionnaire and a debriefing was hold. In the debriefing, the

Table 1. Permutation of the study conditions.

Order	ID: 1	ID: 2	ID: 3	ID: 4
First setup	CAVE	HMD	CAVE	HMD
Second setup	HMD	CAVE	HMD	CAVE

instructor gave the participants feedback on their performance. Finally, the participants were asked about their self-assessment. The same procedure from the briefing until the NASA-TLX was repeated for the other condition. At the end of the study, an interview was hold with the participants.

3.1.5. Technical Issues

During the study, a few technical issues arose in both simulators. In the CAVE, one projector did not work and stayed off for all four participants. Also, some information displays did not work properly. The information placed on them was shifted to the right side, leading to cutting off information. Additionally, the module of the steering wheel was detached and could not be implemented for the study. For complementing this, the participants had to use the left tiller for steering, as the right tiller was not working either. In the HMD setup the virtual handles sometimes got stuck at the minimum or maximum values. Also, the synchronisation between the wing and inside tiller broke in one run. Additionally, the zoom levels of the ECDIS and RADAR was insufficient to display the whole map size on them. This was noted on run-time during the experiment and could only be changed for the last participant. All other participants were told the position for the search by the instructor, so that they could finish their task.

4. Results and Discussion

The gathered data was subdivided into quantitative and qualitative data. For the evaluation, the qualitative part was of higher importance.

4.1. Quantitative Data

The quantitative data consists of a distance estimation, the task completion time and the NASA-TLX results.

4.1.1. Distance Estimation

Participants estimated the distance towards another ship poorly in both setups. The estimations were quite low compared to the actual distance of 440 m. As Figure 5 shows, the closest estimation in the CAVE setup was 370 m, whereas the closest estimation in the HMD setup was 220 m, both by the same participant, with a difference of 150 m. Most estimations in the CAVE were slightly closer to the actual distance (Mean = 200, SD = 118) than in the HMD setup (Mean = 162.5, SD = 58). Only one participant performed better in the HMD than in the CAVE setup. The differences to the actual distance are shown in light grey.

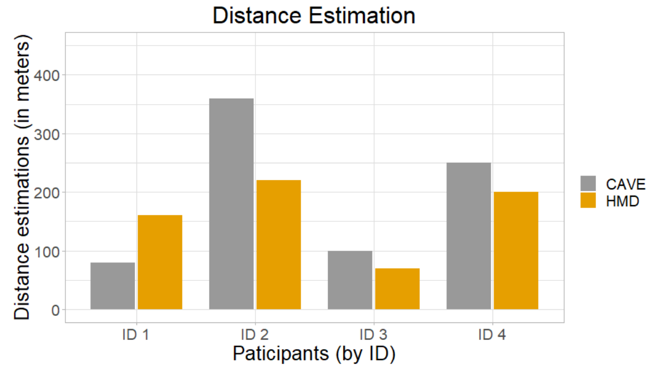

Figure 5. Results of the distance estimation.

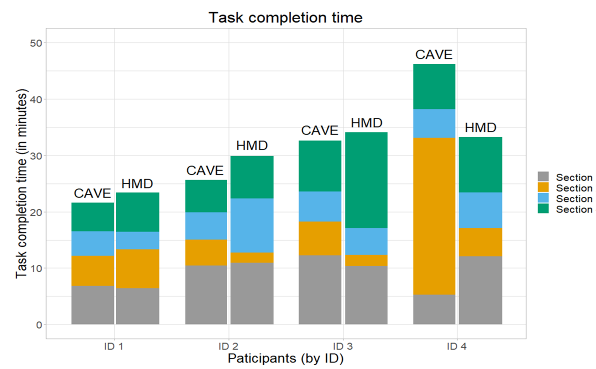

Figure 6. Task completion time.

4.1.2. Task Completion Time

The participants needed less time to solve the whole scenario in the HMD (Mean = 29.31 min, SD = 261) than in the CAVE setup (Mean = 1803.9 s, SD = 499). However, only one participant needed much more time to solve the task in the CAVE (2563.8 s) than in the HMD setup (1941.6 s) with a difference of around 800 s, as the instructor granted another three minutes for finishing the maneuver. The task completion time is shown in Figure 6.

4.1.3. NASA-TLX

Overall, the participants stated their task load slightly lower using the HMD (Mean = 5.04, SD = 1.52) compared to the CAVE (Mean = 5.75, SD = 1.44). Only one participant had a higher workload in the HMD (Mean = 6.17, SD = 1.07) than in the CAVE setup (Mean = 5.5, SD = 3.5). Figure 7 shows the mean scores of the NASA-TLX. In detail, the participants stated the questions as followed. For the mental workload, all participants answered the task was less demanding in the HMD setup (Mean = 5.75, SD = 1.48) compared to the CAVE setup (Mean = 7.75, SD = 1.92). Also the physical workload was rated less demanding in the HMD setup (Mean = 4, SD = 1.87) than in CAVE (Mean = 5, SD = 2.45) except for one participant, who had a higher physical demand in there. Most participants

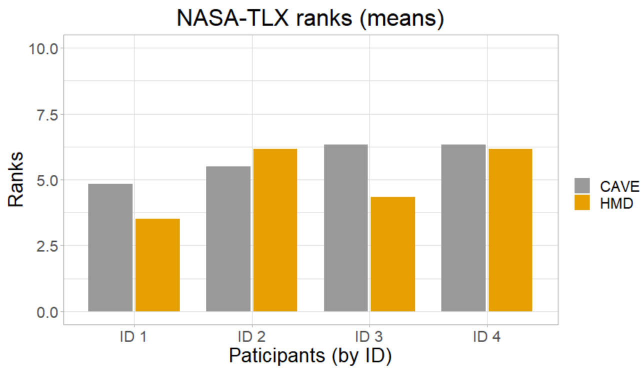

Figure 7. NASA-TLX means.

felt less time pressure in the HMD setup (Mean = 4, SD = 1.58) than in CAVE (Mean = 5, SD = 2.12). Only one participant felt a higher time pressure in the HMD setup. The participants felt slightly more successful using the HMD (Mean = 7.5, SD = 0.87) than solving the task in the CAVE setup (Mean = 7.25, SD = 1.09) with two participants stating a higher success in CAVE and two participants in HMD. All participants had to work equally hard to accomplish the goal in both, the CAVE (Mean = 6, SD = 2.92) and the HMD setup (Mean = 6, SD = 1.87). In the CAVE setup (Mean = 3.5, SD = 2.06), the participants felt slightly more frustrated than using the HMD (Mean = 3, SD = 1.58).

4.2. Qualitative Data

Qualitative data was gathered by observing the participants during the study, both by the supervisor and us. Additionally an interview was held after the experiment.

Overall, all four participants behaved differently compared to each other. Three participants were reliable in both simulators, whereas one participant struggled a lot with the interaction in HMD. The participant had a long settling-in period in the test scene and seemed overwhelmed with using the controller as an interaction tool. In the CAVE setup, the same participant behaved more self-confident, yet needed help by the supervisor in both conditions.

For the interaction with the bridge instruments, there were small differences between the simulators. One difference was the missing realistic haptic feedback of the handles in the HMD setup, which made it slightly less realistic in its usage. In order to this drawback, we could observe that the participants looked down at the instruments each time they adjusted them, whereas in the CAVE setup, they used the handles without a change in sight. For the handles in the HMD setup, the participants struggled with the problem of the blockage. Another difference was the usage of the ECDIS and radar. While in the CAVE setup, the ECDIS and radar was used frequently for navigating, it was rarely used in the HMD, due to the minor functionality. In the HMD setup, the participant rather navigated by sight. Here, the usage of the bridge wings in the HMD setup was found to be very useful, felt more realistic and it brought more immersion into the simulator. Though it felt more realistic, the participants had struggles with recognizing the buoys in the environment in our setup.

During the study, the instructor asked all participants regularly about their speed, course and plans. These questions tested the students situational awareness, according to Øvergård et al. (Øvergård et al., 2015). Solely one participant had a good situation awareness in CAVE and another participant in the HMD setup. Additionally, one participant had a good outstanding awareness in the CAVE setup.

Two participants felt very unconfident in estimating the distance in both conditions. Two participants felt reliable and one could not find much difference to the estimation in real life. The participants used different methods to measure the distance. Some used a reference point or a known distance, like the ship's breadth/length or the distance between two buoys and one participant applied real life experience in addition. One participant estimated just by the view and used no aids. For two participants it felt easier to estimate the distance in the HMD setup, they reasoned it through the immersion and one participant felt the estimation more easily in the CAVE setup.

For the training of students in the future, two participants preferred the commercial SHS, reasoned by the higher realism in the handling and physics. One participant preferred a combination of both setups with different curricula, like the basic navigation on sight or the berthing of a ship for the HMD setup. One participant even preferred the HMD setup. The mentioned reasons were the better immersion and the view. Furthermore, two participants mentioned the limited time students have for practicing in the commercial SHS and that a supplementary simulator, like the one we developed with eliminated drawbacks, is a good possibility for more practice time.

4.3. Discussion

Prior to the study, we expected that the task load would be higher in our simulator. This was reasoned to the expectation of the probably unknown controls. The results instead showed that the task load was higher in the CAVE setup. Reasoned by the participants with the more sophisticated hydro and ship dynamics, inducing more factors to keep in mind and consider during a maneuver.

In contrast to current research on distance estimation in VR (Jamiy and Marsh, 2019), we expected, after experts gave positive feedback to the realistic-perceived view in the HMD setup, that participants would produce better distance estimations in the HMD setup. Whereas

the results showed that the estimation in both setups were poor, in ours slightly worse. Unfortunately, there was no comparable data for the precision of estimations at sea in reality, but due to the comments by the participants of the better-perceived view, we would expect similar estimations.
In our study, the supervisor was only involved in the planning process of the maneuver but not in the experiment design. This resulted in some errors, such as him telling one participant the results of the distance estimation before the interview. Additionally, he was instructed by us to act as it was a normal training session. Being a good instructor means providing the right assistance at the right time. This caused variety in the experiment procedure, because the participants performed differently and had individual problems. This peeked in one run, when the participant struggled with the proposed berthing maneuver due to no prior knowledge, and therefore received three extra minutes to perform and practice the maneuver.
As the results indicate, the resolution did not satisfy the participants. This was a hardware related limitation, since the HTC Vive is limited to 1080 x 1200 pixels per eye - 2160 x 1200 pixels together (HTC, 2020). In the meantime, HMDs with a better resolution and fields of view were released, which we expect would help with a better perception of the buoys and the environment, because the recognition of the colors of the buoys is caused by the way the lighting is applied in the VE and enhanced due to the unsatisfying screen resolution.
Another problem of the experiment were the handles in the HMD setup when they got stuck at their minimum and maximum angles. This problem originated from the used script provided by SteamVR. During the experiment, it caused the ship to become hard to handle and the performance might have been influenced.
With these findings, we could find out that an HMD VR SHS can be used for educational purposes. At this point, the HMD setup already provides the ability to achieve learning goals. Learning goals include getting familiar with bridge equipment, plotting and finding routes, staying on the fairway, learning and applying rules and laws, and improving awareness and decision making. However, we also found out that HMD VR SHS cannot yet be compared to established educational CAVE setups. Although the setup is designed to be as close to a CAVE setup as possible, the physics and hydrodynamics simulation are not sophisticated enough at the moment as well as the missing haptic feedback to enable eyes-free control of e.g. virtual handles. As a result, important maneuvers like COLREG or berthing cannot be performed accurately and not in a preparing way for work life. Nevertheless, the view system and use of the wings outperforms the view in the CAVE and results in higher immersion. Nevertheless, students liked the idea of easier access to simulation time and practice. Therefore, the HMD VR SHS can already be used as a compound tool and is a promising foundation for future development.

5. Conclusion

In order to provide nautical science students with more practice time in a ship handling simulator, we developed a low-cost and flexible alternative prototype. For the vision in VR, we used an HMD and its controller for the interaction. To test its validity, we compared our approach in a within-subject experiment with an already existing and used SHS in a CAVE setup. Our results showed that our implementation brought more immersion when steering a ship by sight, but lack of accurate ship behavior. However, the prototype can be already used as an additional training tool to the CAVE setup. Basic navigation, including keeping track on the route and familiarization with the ship bridge instruments, can be achieved. When adding more complexity, the participants appreciates our setup as a valid standalone tool and would be liked for practicing maneuvers in it.

5.1. Future Work

The current HMD setup cannot be used as a standalone SHS for training and educational purposes. In order to make it a full-fledged simulator several things have to be improved. First of all the lack of realism in terms of ship dynamics and physics shall be addressed. Additionally, a real ECDIS and radar functionality should be added.
Training maneuvers are usually carried out by multiple persons. This requires a multi user-setup for the HMD simulator. Besides training the communication aspect of the ship, maneuvering as a team in a multi-user setup would enable remote training sessions. Splitting up a team spatially would also resemble the reality of ship operations where different crew members work in different parts of the ship.
The proposed VR simulator currently works with a standardized virtual bridge, which is used in every simulated ship. In reality, every bridge is different, ranging from small bridges on ferries up to 50 m wide bridges on large container ships. Without a physical bridge, it is possible to use the actual bridge setups in the VR simulation, potentially increasing realism. On the other hand, participants preferred the haptic feedback of physical equipment in the CAVE more. Consequently, combinations of real ship equipment and VR using HMDs shall be investigated.
Bearing these further implementations in mind, the SHS using an HMD is a reasonable practice tool and provides an alternative to the existing SHS in a CAVE setup.

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