Optical See-Through Mixed Reality as a Cybersickness Mitigation Strategy in Extended Reality Helicopter Flight Simulation

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ABSTRACT

Cybersickness remains an obstacle for the adoption of extended reality in helicopter flight simulation, due to conflicting visual inputs from the virtual environment and vestibular inputs from the actual environment. Reducing this sensory conflict, by means of introducing visual inputs that are coherent with vestibular inputs, is therefore thought to mitigate cybersickness. This study assesses the potential of Optical See-Through Mixed Reality (OST MR), a hybrid approach that visually merges physical cockpit elements with virtual environments, to mitigate sensory conflict and alleviate cybersickness compared to Virtual Reality (VR) helicopter flight simulation. In a human-in-the-loop experiment, five licensed pilots flew a 25-minute course comprising a set of helicopter flight maneuvers in a fixed-base flight simulator with a head-mounted device to display virtual environments. The 25-minute course was flown in a VR condition and an OST MR condition, in a within-subjects setup. The VR condition featured a virtual representation of both the outside world and the cockpit, while the OST MR condition combined the virtual outside world with an OST downward visual of the actual simulator cockpit and the pilot's own body. The cybersickness development was evaluated through an 11-point sickness scale, and a motion sickness questionnaire. The standard deviation of the HMD position was analyzed as metric for the amount of head motion, to assess the impact of the increased downview in the OST MR condition. No notable differences between the experiment conditions were found for the sickness scores and sickness questionnaire responses, even though participants exhibited less head motion in the OST MR condition. The results suggest that the OST downview did not meaningfully contribute to visual motion perception for reducing the visual-vestibular sensory conflict. These findings demonstrate that visual cybersickness mitigation measures should be concentrated on the area of the field-of-view that elicits the strongest visual motion perception response.

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INTRODUCTION

Incorporating Extended Reality (XR) into flight simulation offers a promising opportunity to render flight crew training more versatile and cost-effective when compared to traditional flight simulation methods. XR - an umbrella term that spans concepts such as Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) - allows for a software-based projection of a flight simulation environment by means of a Head Mounted Display (HMD) (Rauschnabel, Felix, Hinsch, Shahab, & Alt, 2022). Accordingly, XR provides the possibility to eliminate costly flight simulation components, such as a collimated visual display system or certain cockpit hardware, in favor of virtual equivalents projected on the HMD. The benefits of XR in flight simulation are increasingly recognized by the aviation industry for this reason, which has spurred XR flight simulation to become more commonplace in recent years, particularly in the form of VR flight simulation (European Union Aviation Safety Agency (EASA), 2023), (Oh C. G., 2020), (Dymora, Kowal, Mazurek, & Romana, 2021).

However, the inclusion of XR in flight simulation for flight crew training also introduces challenges. One such challenge is the increased likelihood of experiencing cybersickness, defined as a form of visually-induced motion sickness in virtual environments (NATO Science & Technology, 2021), (Kim, Kim, Kim, Ko, & Kim, 2023), (Oh & Son, 2022). This could in turn compromise the efficacy of VR-based flight crew training and thereby jeopardize the opportunities that XR flight simulation offers (Chang, Kim, & Yoo, 2020). Addressing this heightened risk of experiencing cybersickness is therefore essential for optimally leveraging the advantages of the application of XR in flight simulation for flight crew training.

A wide variety of causes for cybersickness is known to exist, ranging from technological factors innate to HMDs, such as excessive latency, operational aberrations, and alterations in the field-of-view, to differences in sensory inputs caused by the introduction of virtual environments (Oh & Son, 2022), (NATO Science & Technology, 2021). The relationship between the difference in sensory inputs and cybersickness, being a form of motion sickness, is explained by the sensory conflict theory, which stipulates that an unexpected sensory conflict between the motion perception from visual stimuli and the motion sensed by the vestibular system can cause cybersickness (Chang, Kim, & Yoo, 2020), (Palmisano, Allison, & Kim, 2020), (Reason & Brand, 1977), (Lawson, 2014), (Zelie & Qadeer, 2019). While it does not tackle the sickening effect of the HMD technological factors described above, mitigating the sensory conflict between the visual sensory stimuli from the virtual environment and the vestibular sensory inputs from the real-world environment is therefore seen as a key strategy in combating cybersickness in XR-based training systems (Ng, Chan, & Lau, 2020).

Within an XR-based training environment, implementations of this sensory conflict mitigation strategy that have shown promise include the synchronization of visual-vestibular motion by means of a motion platform (Porcino, Clua, Trevisan, Vasconselos, & Valente, 2017), providing visual rest-frame cueing (Weinrich, Weidner, Obremski, & Israel, 2018), and the visual blending of the real and virtual environments as a form of MR to facilitate visual sensory inputs that are coherent with vestibular sensory inputs (Englebert, Marsman, & Crijnen, 2023). A noteworthy complication of the latter strategy, however, is that this form of MR can be intrusive for the immersion in the virtual environment, since the visual blending inhibits the perception of the virtual environment. In the context of pilot training, it has been demonstrated that, despite alleviating feelings of cybersickness, this can lead to a deterioration in pilot performance and can as such affect training effectiveness in XR flight simulation (Englebert, Marsman, & Crijnen, 2023).

In order to minimize these deteriorations in immersion and to make MR a viable cybersickness mitigation strategy in XR flight simulation, it is paramount to optimize the cueing of visual sensory inputs from the real-world environment for the purpose of reducing the visual-vestibular sensory conflict. Since such an optimized form of MR should not impede on the ability to perceive the virtual environment to prevent negative effects for pilot performance and training effectiveness, the blending of the virtual outside world with the real-world environment should be carefully managed. A possible implementation of MR that takes this into account could be combining a purely virtual outside environment, allowing for uninterrupted perception of the virtual task environment, with a real-world visual of the actual cockpit and the pilot's own body that provides a visual reference that corresponds with the vestibular sensory stimuli. It is therefore thought that combining a completely virtual outside world in which the flying tasks are performed with a downview of a real, physical cockpit as an alternative form of MR could achieve similar cybersickness mitigation effects, while lessening the negative effects for pilot performance and training effectiveness.

In such an MR solution, the down view of the actual cockpit and the surrounding environment provides visual sensory inputs that are coherent with the vestibular sensory inputs, thereby negating the visual-vestibular sensory conflict, while the completely virtual outside would allow for optimal perception of the environment in which the flying tasks are performed. An additional factor that could positively contribute to cybersickness mitigation is the perception of the own body, as it has been demonstrated that first-person body perception in virtual environments can improve the sense of presence and agency, which can contribute to feelings of comfort (Nakano, et al., 2021), (Kokkinara, Kilteni, Blom, & Slater, 2016). Moreover, perception of the own body could elicit additional sensory feedback as a result of being able to perceive manual control inputs, which could lead to more accurate motion anticipation and a consequent decrease in discomfort (Abtahi, Hough, Landay, & Follmer, 2022).

For presenting real-world visual information in XR, it is important to note that multiple technological implementations could be considered, as a result of the variability in available HMDs. These technological implementations, however, differ in terms of the suitability for cybersickness mitigation through sensory conflict reduction (Porcino, Clua, Trevisan, Vasconselos, & Valente, 2017). The options for these technological implementations can categorized in terms of the two most common variants of HMDs, those being Video See-Through (VST) and Optical See-Through (OST) devices. The primary distinctions between VST and OST devices lie in their hardware and their intended XR experience. VST employs cameras to stream real-world visuals onto the internal display of the HMD. Conversely, OST utilizes transparent lenses to present the unaltered real-world view, allowing digital content to be overlaid and rendered through optics (Drascic & Milgram, 1996). Since VST devices typically introduce latency and more severe optical aberrations than OST devices, which in turn can inherently result in more severe cybersickness, OST devices are deemed to be better suited for presenting visual sensory information from the real-world environment in an effort to reduce feelings of cybersickness (Xia, Zhang, Ma, Cheng, & Hu, 2023), (Nabiyouni, Scerbo, Bowman, & Hollerer, 2017).

The objective of this research is to explore the effectiveness of Optical See-Through Mixed Reality (OST MR), which combines a virtual outside world with a downview of a real-world cockpit, for cybersickness mitigation in XR helicopter flight simulation. This will be investigated by means of a human-in-the-loop experiment, in which the participants will complete a predefined course consisting of various helicopter flying tasks in a virtual environment, where the OST MR solution is compared with regular VR. First, a description of the method for this human-in-the-loop experiment is provided, followed by the experiment results. The interpretation and discussion of these results are provided next, after which the conclusions with regard to OST MR as a cybersickness mitigation strategy in XR helicopter flight simulation are presented.

METHOD

Participants

The experiment participants consisted of five pilots who were all in possession of either military or commercial helicopter pilot license, four of which reported also being or having been a flight instructor or test pilot. The age of the five pilots that finished the experiment varied between 41 and 63 years and a mean age of 49. Four of them were professional pilots with flight hours ranging between 2700 and 8300 and one was a general aviation pilot, with 180 flight hours on a Bell47. It is important to stress the small sample size for the results, given the small number of participants, see also the acknowledgements at the end of this paper.

To identify variations among the participants in motion sickness susceptibility, as a reference for their susceptibility to cybersickness, the participants completed the Motion Sickness Susceptibility Questionnaire (MSSQ), developed by Golding (Golding, 2006), prior to participating in the experiment. The participants reported a median MSSQ score of 2 ($\mu = 1.75$, $\sigma = 0.671$) which falls between the 10^{th} and 20^{th} percentile for motion sickness susceptibility, implying below-average susceptibility to motion sickness (Golding, 2006). In addition, one participant reported having experienced cybersickness in VR flight simulators in the previous ten years. All participants were asked not to consume alcohol, or products with comparable physical effects that could affect the results, 24 hours prior to participating in the experiment.

Apparatus

The experiment was performed in the Helicopter Pilot Station (HPS) simulation facility, a fixed-base helicopter flight simulator that provides a generic cockpit environment with high-fidelity flight controls for two crew members, see Figure 1. Instead of using the HPS visual display system, the virtual outside environment was projected by means of an HMD that combines a forward-looking 5.5” LCD display for projecting the virtual environment with an OST downview window that enables the real-world environment to be perceived. The HMD has a refresh rate of 60 Hz, a horizontal field-of-view of 120 degrees, and a vertical field-of-view of 45 degrees if only the LCD display is used, which increases to a vertical field-of-view of 72 degrees when combined with the OST downview.

The cockpit instruments visualized on the HPS screens, and in the virtual environment comprise only a functional primary flight display, featuring an artificial horizon, an altimeter, an airspeed indicator, and a compass rose. Other cockpit instruments were generic and non-functional. The flight model that used during the simulation was an in-house-developed AS532 Cougar helicopter model.

Figure 1: Helicopter Pilot Station and HMD experiment setup

Experiment Conditions

The independent measures comprise the two different variants of XR, i.e., the regular VR as the baseline experiment condition and the OST MR experiment condition, where the VR and OST MR conditions are pairwise compared in a within-subjects setup. For the VR condition, the HMD's OST downview windows are blocked by covering it with a light-blocking fabric, leaving only the LCD display for projecting the virtual environment. Consequently, both the outside world and the cockpit, including the cockpit instruments, are completely virtual in the VR condition.

In the OST MR condition, the OST downview allows for visually perceiving the real HPS cockpit and the pilot’s own body in the lower part of the vertical field-of-view. In this setup, it is important that discontinuities when vertically moving the head between the cockpit projected by the LCD displays in the upper part of the vertical field-of-view, and the physical cockpit seen through the OST downview in the lower part of the vertical field-of-view are prevented. As such, the physical HPS cockpit should be displayed by the LCD display in this setup, depending on the pitch angle of the head.

To facilitate this, the position of the physical cockpit with respect to the HMD is determined using SteamVR head tracking. Depending on the relative position of the HMD with respect to the physical cockpit, the physical cockpit is made visible by masking the virtual cockpit at the viewing angle above the OST downview, and by subsequently projecting a video stream of the physical HPS cockpit onto the LCD display. Hence, for the OST MR condition, the cockpit is the real-world physical cockpit of the HPS, seen either through the HMD's OST downview window or by the LCD display, depending on the relative head position. Effectively, this allows for the perception of the real cockpit displays, flight controls and the own body through the OST downview window, where discontinuities in the view of the cockpit displays are prevented by projecting the HPS cockpit on a masked virtual cockpit in the LCD display depending on the relative head position. A consequence of this setup is that a difference exists between the OST MR and VR conditions in terms of the vertical field-of-view, as a result of blocking the OST downview in the VR condition to prevent any real-world visual perception and render the visual scene fully virtual. The implications for this difference in the vertical field-of-view on cybersickness development, and the consequent interpretation of the results, is discussed in more detail in the Dependent Measures and Data Analysis subsection.

The out-of-the-window view in the OST MR condition projected by the LCD display is still completely virtual, and is identical to the virtual outside world also used in the VR condition. Visual representations of the view at the pilot's eye reference point in both experiment conditions are presented in Figure 2 and Figure 3 for the VR and OST MR experiment conditions, respectively.

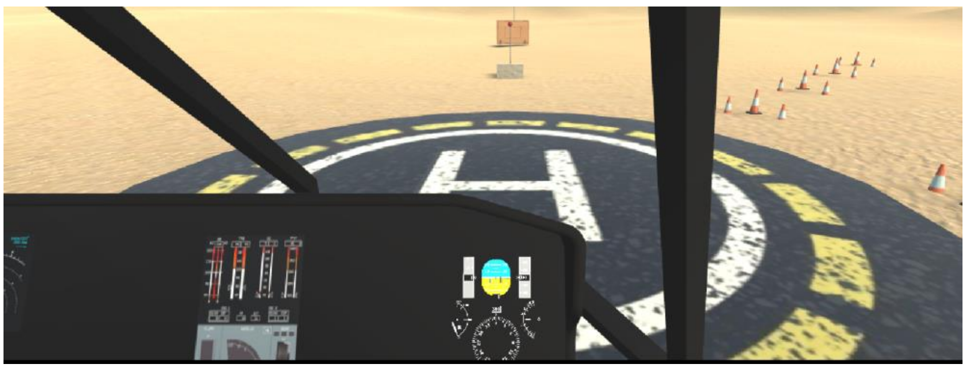

Figure 2: Virtual cockpit and virtual outside world in the VR condition

Figure 3: Mixed reality optical see-through cockpit and virtual outside world in the MR OST condition. The white horizontal line denotes the boundary the LCD display and the optical see-through downview.

Scenario

The experiment featured a helicopter flying scenario with an approximate duration of 25 minutes in a virtual environment. The virtual environment is created in Unity and consists of an approximately 5km by 5km island featuring a course comprising a predetermined set of flight maneuvers. These flight maneuvers are a series of Mission

Task Elements (MTEs) from the ADS-33 (Baskett, 2000), which prescribes standard maneuvers used to assess the handling qualities of rotorcraft, and as such features a broad spectrum of rotorcraft flight tasks. As the MTEs are used for handling qualities evaluation, they are associated with a set of performance parameters, such as the desired speed range, altitude range, or maneuver timings. While these performance indicators normally are criteria to assess the rotorcraft handling quality, in this experiment the performance indicators are solely used to describe the MTEs in detail to the participants, leaving little room for variation between the participants' MTE approaches.
Excluding take-off and landing, nine MTEs, distributed over several parts of the island were executed. The MTE's are described below (Baskett, 2000):

1) Hover: A stable hover at an altitude of 15 feet. The hover is performed over a helipad, with the goal of maintaining a stable hover for 30 seconds.
2) Depart-Abort: An acceleration to a maximum airspeed of 50 knots followed by a rapid deceleration back to hovering flight over an 800-meter track, while maintaining an altitude lower than 35 feet.
3) Slalom: A sequence of lateral direction changes, while flying level in unaccelerated flight with an airspeed above 40 knots and an altitude below 100 feet. The slalom is performed over the grey runway on the North side of the island depicted in Figure 4.
4) Sloped landing: A 10-degree nose-up landing in the mountainous area of the virtual island, following a vertical descent while maintaining a constant heading.
5) Vertical re-mask: An abrupt vertical descent from an altitude of 75 feet to an altitude of 25 feet within 6 seconds.
6) Lateral sidestep: A lateral acceleration followed by a deceleration over a 300-meter track, performed within 15 seconds and while maintaining an altitude below 25 feet. The lateral sidestep was combined with the vertical re-mask as a single maneuver during the experiment.
7) Hovering turn: Above the helipad, two 180-degree turns, clockwise and counterclockwise, starting from a heading of 90 degrees and finishing at a heading of 270 degrees, while maintaining an altitude below 15 feet.
8) Pirouette: A 360-degree lateral translation over a circular track with a predefined radius while keeping the heading of the helicopter fixed with respect to a reference symbol in the center of the circular track. Since the pirouette MTE is expected to be the most sickening MTE due to the continuous lateral accelerations and rotations, which are known to contribute significantly to visually-induced motion sickness (Keshavarz, Riecke, Hettinger, & Campos, 2015), (Bos, Bles, & Groen, 2008), the pirouette is described in more detail below.

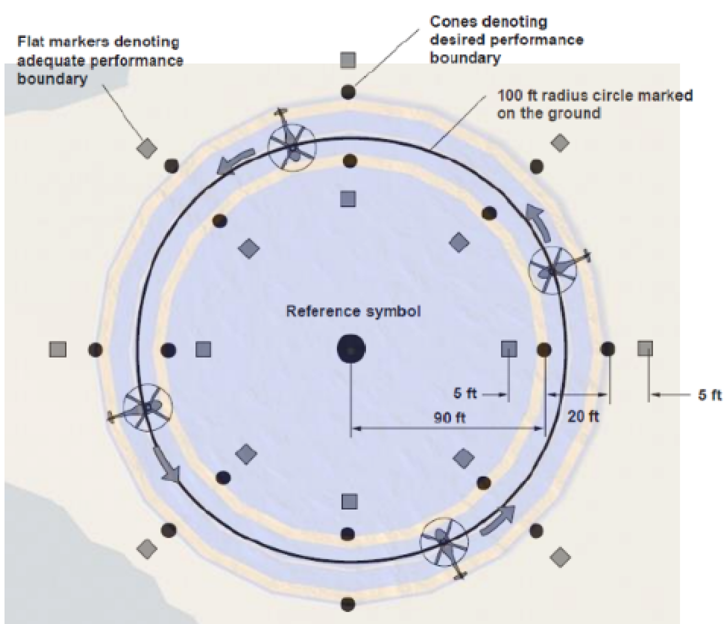

Figure 4: Pirouette MTE procedures and performance limits (Baskett, 2000), combined with the virtual environment implementation of the pirouette MTE course

The pirouette MTE is performed both in clockwise and counterclockwise direction over the virtual pirouette course shown in Figure 4. As denoted in Figure 4, the pirouette imposes performance restrictions on the flown radius, allowing for deviations from the radius centerline lower than 10 feet. The orange lines in Figure 5 indicate the inner- and outer boundaries of the specified radius, where the middle line is the nominal path.

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In order to reach the approximate target scenario time of 25 minutes, the slalom, vertical re-mask, lateral sidestep, hovering turn, and pirouette MTEs were repeated after finishing the MTE sequence outlined above.

Procedures

Before participating in the experiment, the participants were asked to complete a set of questionnaires, containing the MSSQ as well as questionnaires on experience with (XR) flight simulation and pre-existing sickness symptoms. The participants were then given a safety briefing, they signed an informed consent form, and they were instructed on the use of the MIsery SCale (MISC), which is an 11-point sickness scale that quantifies motion sickness severity based on the type and severity of common motion sickness symptoms (Bos, MacKinnon, & Patterson, 2006). The MISC was used to track the cybersickness development over the course of the experiment conditions.

After having completed the pre-experiment procedures, the participants were instructed to sit in the right seat of the HPS, as shown in Figure 1, after which they were allowed to fly a familiarization run to get accustomed with the flight controls and the simulated environment, which ended when the participants indicated that they were ready to start with the actual experiment. To prevent bias towards any of the two experiment conditions, the familiarization run was performed using the projector visual display system, instead of with the HMD.

Next, the participants started with one of the two experiment conditions, where the experiment condition order was pseudo-randomized to prevent order effects. During the experiment conditions, the participants verbally indicated over the HPS intercom when they were about to start an MTE from the MTE sequence described above, by saying ‘ON condition’. After having the completed the MTE, the participants reported back to the experiment operator by saying ‘OFF condition’ to signify that the MTE had been completed. Upon hearing ‘OFF’ condition, the experiment operator asked the participant for their MISC score. Since two experiment conditions were performed in a single day, the experiment condition was aborted when a MISC score of 5 was reported, indicating severe motion sickness symptoms, but no nausea, or when the participants indicated that they wanted to abort the session early. In case of an experiment condition that was aborted prematurely, it was assumed that the MISC score would remain the last reported MISC score for the remainder of the session, in order to facilitate a consistent analysis of the MISC scores.

After each experiment condition, the participants completed the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993), as a means to gain additional insight into the type and severity of the motion sickness symptoms that were experienced. To prevent cybersickness from the first experiment condition affecting the cybersickness development in the second experiment condition, the participants subsequently rested until they reported a MISC score of 0 again, indicating that they did not feel any motion sickness symptoms whatsoever anymore, before starting the second experiment condition. The procedures for the second experiment condition were identical to those for the first experiment session. When the participants finished the second experiment condition, they again completed the SSQ, and they were interviewed on their subjective experience and their preference for the OST MR or the VR setup in terms of training value and user comfort.

Dependent Measures and Data Analysis

1) MSSQ Scores: The susceptibility of the participants to motion sickness, as a reference for their cybersickness susceptibility, was evaluated by means of MSSQ scores.
2) MISC Scores: The cybersickness development was evaluated using MISC scores (Bos, MacKinnon, & Patterson, 2006), where a MISC score was provided after the completion of every MTE. The MISC scores are analyzed by visualizing the MISC score development after each MTE, by means of the mean and standard deviation of the reported MISC scores, as well as by examining the maximum MISC scores reported by the participants per experiment condition.
3) Simulator Sickness Questionnaire: To crosscheck and supplement the MISC scores, the SSQ was administered after each experiment session. The SSQ is evaluated by means of the SSQ score, see also (Walter, et al., 2019).

4) HMD position standard deviations: Provided that the vertical field-of-view in the VR condition is smaller than in the OST MR condition, as a result of covering the downward display of the OST HMD, it is expected that participants will need to move their head more to maintain situational awareness while executing the MTEs. This greater amount of head motion is expected to exacerbate cybersickness, due to the technological factors inherent to HMDs that can cause cybersickness in combination with head motion, such as latency and the parallax effect (Drascic & Milgram, 1996), and increased visual motion perception.

   As discussed before, visual information can induce feelings of motion sickness as a result of the perception of angular and linear velocity through circular and linear optic flow (Bos, Bles, & Hosman, 2001), (Lawson, 2014). The perceived self-motion resulting from circular and linear optic flow in turn is referred to as vection, which as such induces visual motion perception (Cornilleau-Pérès & Gielen, 1996), (Bos, Bles, & Groen, 2008), (Keshavarz, Riecke, Hettinger, & Campos, 2015). Accordingly, this increased head movement would lead to more vection and therefore an increase in the visually-induced motion perception, aggravating the visual-vestibular conflict as a result of the greater mismatch between visual and vestibular sensory inputs, thereby worsening the cybersickness severity.

   The standard deviations of the HMD position, as a metric for the amount of head motion, will be analyzed and compared to the MISC scores, in order to identify whether there is indeed a correlation between the level of cybersickness and the amount of head motion. The standard deviation of the HMD position was selected as a metric since a higher standard deviation indicates greater variation in the HMD position measurements, which is indicative of the amount of head motion. This analysis will be performed for the pirouette MTE, since this MTE is considered to be the most dynamic and would as such lead to the most visually-induced motion perception, and is and is known to require the most gaze shifting between the outside world and the cockpit displays due to the altitude and speed requirements. As such, it is expected that the pirouette MTE will elicit the greatest amount of head motion in order to maintain situational awareness.

Three measures collected during the experiment were omitted from results presented in the next section. First, metrics for pilot performance, for instance in terms of the deviations from the MTE reference flight trajectories, were recorded, but not included in this paper due to the page limit, for which it was decided to focus on the cybersickness results. Secondly, the postural stability measurements collected before and after both conditions. These measurements showed small and inconsistent differences between the measurement taken before and after the conditions. In combination with the small number of participants, the collected measurements were noisy to (statistically) analyze. Finally, electro-dermal activity measurement were collected from participants' foreheads. These measurements showed an increase over time during the conditions. However, it cannot be concluded whether this increase in activity is due to an increase in cybersickness.

Hypotheses

Based on the research goal and background described in the Introduction, the following hypotheses were formulated. Due to the small number of participants, it is again important to stress that there hypotheses are solely exploratory, and should be interpreted accordingly.

- H.1) OST MR, featuring a virtual environment and a real-world cockpit perceived through an OST HMD, reduces cybersickness severity compared to Virtual Reality in helicopter flight simulation.
- H.2) The increased vertical field-of-view in the OST MR experiment condition reduces head motion compared to the VR experiment condition, correlating with lower levels of cybersickness in the OST MR experiment condition.

RESULTS

Cybersickness

The progression of the cybersickness development over the course of the experiment conditions, expressed through the mean MISC scores and accompanying standard deviations for each MTE, is visualized in Figure 6. It is clear from Figure 6 that the differences between the experiment conditions for the mean MISC scores and standard deviations are minimal throughout the scenario, where the VR condition only appears to be slightly more sickening in the early stages of the scenario. Towards the end of the scenario, however, the mean MISC scores are approximately equal between the experiment conditions.

The minimal difference between the experiment conditions is also found when comparing the maximum MISC scores reported by the five participants per experiment condition. The median maximum MISC score for the VR condition was 4 (μ = 3.20, σ = 1.17), versus a median maximum MISC score of 3 for the OST MR condition (μ = 3.20, σ = 1.17). Despite the higher median maximum MISC score, the mean maximum MISC scores are identical, underscoring the notion that minimal difference in cybersickness severity exist based on the reported MISC scores.

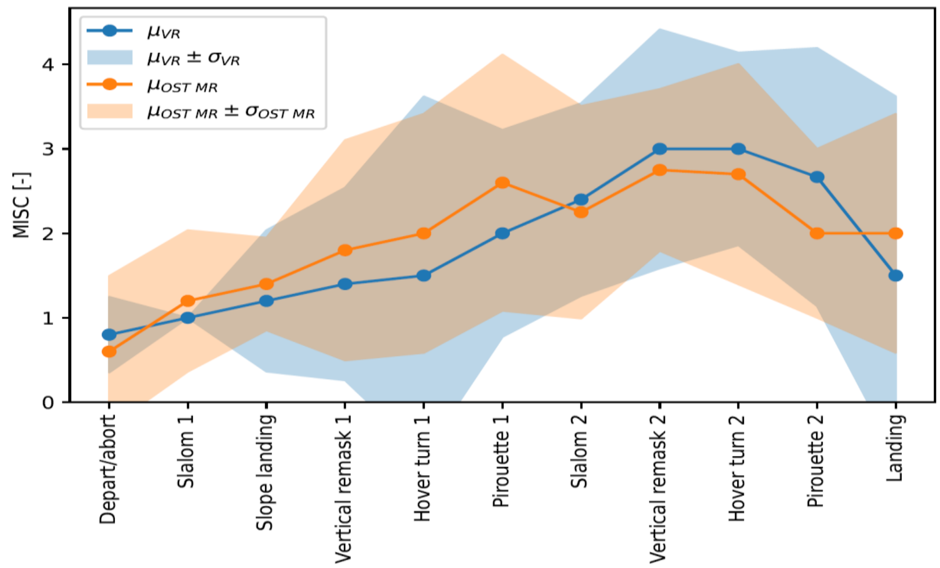

Figure 5: Mean and standard deviation MISC scores after each MTE

The SSQ scores, computed by means of the weighted scoring procedure for the nausea, oculomotor, and disorientation categories described by Walter et al. (2019), for both experiment conditions are presented in Table 1, per participant and in terms of the mean and standard deviation of the SSQ scores per experiment condition. Table 1 shows that individual differences between participants exist in terms of the SSQ score and the corresponding cybersickness severity between the conditions: participant P1 seems to have experienced more severe cybersickness in the VR condition, participants P2 and P3 experienced approximately the same cybersickness severity levels in both conditions, and participants P4 and P5 experienced more cybersickness in the OST MR condition. The mean SSQ scores presented in Table 1, however, show a slightly higher mean SSQ score for the OST MR condition, than for the VR condition, implying that the OST MR condition was overall slightly more sickening, based on the SSQ scores.

Table 1: SSQ scores per participant, and the participant mean and standard deviation

	SSQ Scores						
	P1	**P2**	**P3**	**P4**	**P5**	**μ**	**σ**
VR	29.9	44.9	67.3	7.48	44.88	38.9	19.7
OST MR	15.0	44.9	67.0	18.7	74.8	44.1	24.4

Head Motion

The head motion analysis is performed by analyzing the HMD position standard deviations for the pirouette MTEs, for which it is expected that the limited vertical field-of-view in the VR condition will prompt predominantly more lateral and vertical head motion to keep track of the cockpit instruments and the pirouette track, compared to the OST MR condition. Hence, the standard deviations of the HMD lateral position 'y' and the HMD vertical position 'z' are assessed to gauge the difference in the amount of head motion between the experiment conditions.

The HMD position measurements were sampled at a rate of 10 Hz, for the duration of the executed pirouette MTEs. Ten pirouette MTEs are analyzed in total per experiment condition, since the five participants each executed two pirouette MTEs within each condition. The results for the lateral HMD position standard deviation and the vertical HMD position standard deviation, combined with the MISC scores reported upon the completion of the pirouette MTEs, are presented in Figure 6 and Figure 7, respectively.

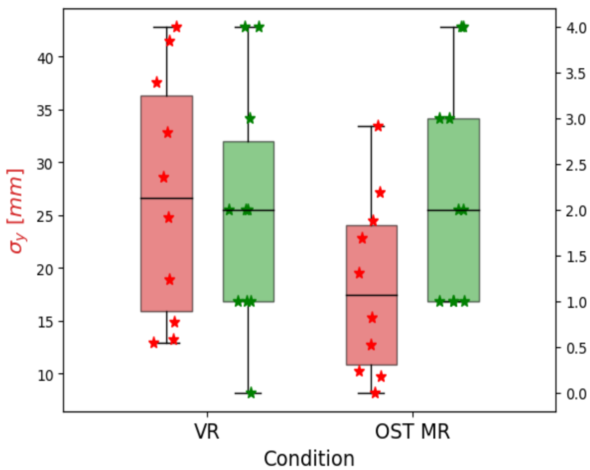

Figure 6: Pirouette MTE lateral HMD position standard deviation and MISC

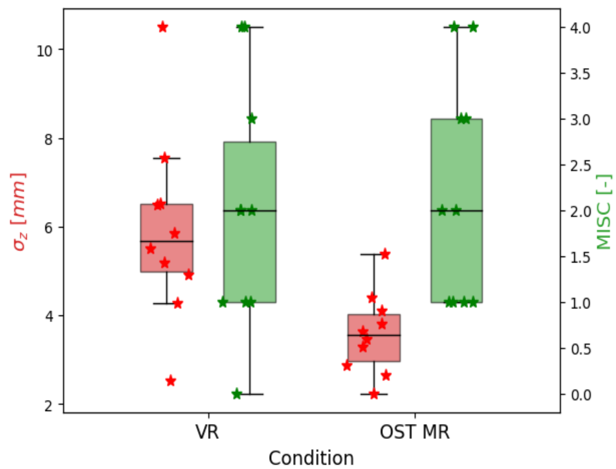

Figure 7: Pirouette MTE vertical HMD position standard deviation and MISC

From Figure 6 and Figure 7, it is apparent that a difference exists between the VR and OST MR conditions for the lateral and vertical HMD position standard deviations, with higher standard deviations in the VR conditions, while no observable difference can be noted between the conditions for the reported MISC scores. These observations are corroborated by paired t-tests, which confirm that a statistically significant difference exists for the vertical HMD position standard deviations 'σ_z' between the VR condition (μ = 5.93 mm, σ = 2.01 mm) and the OST MR condition (μ = 3.58 mm, σ = 0.865 mm); $t(9) = 3.72$, p =0.00478, as well as for the lateral HMD position standard deviations 'σ_y' between the VR condition (μ = 26.8 mm, σ = 11.0 mm) and the OST MR condition (μ = 18.4 mm, σ = 8.04 mm); t(9) = 2.41, p =0.0395. Despite the small sample size, it was found that the within-pair correlation is high ($r > 0.8$) for the lateral and vertical HMD position standard deviations, implying sufficient statistical power (De Winter, 2013).

The observation that differences in the amount of head motion do not correspond to differences in the reported MISC scores is confirmed by a correlation analysis, which shows a weak correlation of the reported MISC scores with both the lateral HMD position standard deviations 'σ_y' (r = -0.239) as well as the vertical HMD position standard deviations 'σ_z' (r = -0.0885).

DISCUSSION

The aim of this research was to investigate the impact of OST MR, combining a virtual outside world with a OST visual of the real cockpit and the pilot's body, on the development of cybersickness compared to VR for helicopter flight simulation. Since the OST MR provides a visual reference to the actual environment that provides visual sensory inputs that correspond with vestibular sensory inputs, it was expected that the visual-vestibular sensory conflict would be smaller in the OST MR condition than in the VR condition, resulting in less severe cybersickness when using OST MR compared to VR (Hypothesis H.1). Since the OST MR condition featured an enlarged vertical field-of-view compared to the VR condition, owing to the OST downview in the OST MR condition that was not present in the VR condition, it was expected that more head motion would be required in the VR condition to maintain adequate situational awareness and to execute certain flight maneuvers. This greater head motion, in turn, was expected to elicit more severe cybersickness, due to technological factors inherent to HMDs that provoke cybersickness in combination with head motion, and as a result of the increased vection and resulting visual motion sensation, which would lead to greater visual-vestibular conflict (Hypothesis H.2).

In experiment conditions consisting of a predetermined track of helicopter flight maneuvers in a virtual environment, the cybersickness development was evaluated by having the participants verbally report their MISC score after each flight maneuver. In an effort to reflect on the overall cybersickness symptoms and the accompanying symptom severities that were experienced, the participants additionally answered the SSQ after the completion of each experiment condition. Even though individual differences were found between the participants in their SSQ scores, where some participants seemed to favor the OST MR or the VR condition, no notable difference in the mean MISC scores and mean SSQ scores was found between the OST MR and VR conditions. From these results, it can be asserted that OST MR did not mitigate cybersickness compared VR in the virtual helicopter flight simulation scenario, thereby rejecting Hypothesis H.1. Despite the overall difference between the mean MISC scores and SSQ scores being minimal, the individual differences between the participants could suggest that the effectiveness of, and preference for, cybersickness mitigation measures is, at least partly, subjective.

It was expected that the difference in head motion required for proper task execution would be greatest in flight maneuvers that are highly dynamic and that prompt frequent gaze shifting between the virtual world and the cockpit instruments. Accordingly, it was decided to use the head motion data for the pirouette MTE for the head motion analysis. As a metric for the amount of head motion, the vertical and lateral HMD position standard deviations were analyzed, as it was expected that the greatest difference in head motion resulting from the difference in vertical field-of-view would occur in these axes. The results demonstrated that statistically significant differences exist between the experiment conditions for the lateral and vertical HMD position standard deviations, where larger standard deviations were noted for the VR condition in both lateral and vertical axes. This finding signifies that the larger vertical field-of-view in the OST MR condition did indeed result in less head motion than in the VR condition. Despite these differences in head motion between the two conditions, no difference was observed for the corresponding MISC scores that were reported after the completion of the pirouette MTEs. As such, it can be concluded that, while the difference in the vertical field-of-view affected the amount of head motion, the difference in head motion does not correlate with a difference in cybersickness severity between the experiment conditions. Hypothesis H.2 is therefore rejected as well.

These results are corroborated by the comments the participants made after completing the experiment, stating that the MTEs were executed primarily using visual references in the virtual outside world, as the additional downview in the OST MR setup did not provide useful additional visual cues relative to the VR setup. One participant did report that vertically moving the head to scan the instruments when necessary was more uncomfortable in VR than in OST MR due to the lag between the head motion and the virtual image displayed by the HMD. This, however, is arguably more related to the inherent difference in lag between OST and VR HMDs, and not to the blending of a virtual outside world with an OST downview as a particular mitigating measure for cybersickness.

A possible explanation for the lack of cybersickness mitigation in the proposed OST MR solution compared to VR could there be that the periphery of the vertical field-of-view does not significantly contribute to the visually-induced motion perception. More specifically, it has been demonstrated that circular vection induced by a moving virtual environment does not significantly differ between an unrestricted vertical field-of-view and a vertical field-of-view that is limited to 50 degrees, implying that vertical field-of-view angles larger than this envelope do not meaningfully contribute to visual motion perception (Mohler, Riecke, & Bülthoff, 2005). Consequently, it is hypothesized that mitigating measures applied to the peripheral areas of the vertical field-of-view, like in the proposed OST MR solution, have minimal impact on reducing the visual-vestibular sensory conflict and due to the lack, thus, do not meaningfully contribute to alleviating cybersickness. This insight suggests that visual measures aimed at mitigating cybersickness should be concentrated in the areas of the field-of-view that most influence the perception of visually-induced motion.

However, it should be noted that inadequate design of mitigating measures for cybersickness, such as the ‘rest-frame cueing’ proposed in (NATO Science & Technology, 2021), in the regions of the field-of-view that most contribute to visual motion perception can lead to a deterioration in immersion. It has been demonstrated that such deteriorations in immersion due to improper rest-frame cueing design, for instance in the form of visually blending the real and virtual environments throughout the field-of-view, can negatively affect training effectiveness and pilot experience (Englebert, Marsman, & Crijnen, 2023). These findings therefore provide guidelines for the design of visual mitigation measures for cybersickness in XR helicopter flight simulation, where 1) it is paramount that the mitigating measures act in the regions of the field-of-view that notably affect visual motion perception, and 2) the optimization of the apparent trade-off between comfort and immersion for these mitigation measures should be considered.

CONCLUSION

The aim of this research was to investigate the impact of OST MR, combining a virtual outside world with an OST downview visual of the real cockpit and the pilot's body, on the development of cybersickness compared to VR, for extended reality helicopter flight simulation. While it was expected that OST MR would mitigate cybersickness compared to VR, no difference between OST MR and VR was observed in sickness ratings for both conditions acquired in a human-in-the-loop experiment. It should be noted that the number of participants was limited, and that these results should be consolidated in a human-in-the-loop experiment featuring a larger sample size. A plausible explanation for this outcome is that the periphery of the vertical field-of-view, corresponding to the additional downview in OST MR, does not significantly influence visually-induced motion perception. Consequently, effective cybersickness mitigation measures should target the areas of the field-of-view that most impact visual motion perception, without significantly diminishing immersion and user experience. The findings from this study therefore provide guidelines for the design of visual mitigation measures for cybersickness in extended reality helicopter flight simulation, stressing the importance of concentrating the mitigating measures in the area of the field-of-view that contributes most to visual motion perception, while preserving immersion to maintain training effectiveness and pilot experience. The application of these guidelines for cybersickness mitigation measures design could therefore constitute a potential future research avenue.

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