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# Rest-Frame Cueing for Cybersickness Mitigation in Virtual Reality Helicopter Flight Simulation

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## ABSTRACT

The integration of Virtual Reality (VR) into flight simulation offers the prospect of cost-effective training but also introduces challenges, most notably an increased likelihood of experiencing cybersickness. Addressing this issue is crucial, given its potential impact on the effectiveness of VR-based training. Prior research has shown promise in utilizing rest-frame cueing, in which a visual reference within VR is aligned with the real-world environment, as a cybersickness mitigation strategy, for instance through the use of Mixed Reality (MR). This study explores the use of Virtual Reference Grids (VRGs) as a form of rest-frame cueing in VR to mitigate cybersickness during helicopter flight simulation, also compared to MR as a form of rest-frame cueing. A human-in-the-loop experiment involved four Royal Dutch Air Force helicopter pilots executing predetermined flight maneuvers in a virtual environment. The experiment compared the impact of VRG and MR rest-frame cueing to regular VR as a baseline, utilizing the 11-point Misery Scale to measure subjective cybersickness levels. Contrary to the findings for MR, the VRG did not reduce cybersickness; instead, it led to a minor increase in discomfort. However, the use of VRG proved less detrimental to pilot performance than MR. Participant feedback suggested that limited cognitive awareness and understanding of the fixed nature of the VRG with respect to the actual environment contributed to its negative impact on cybersickness mitigation. These findings underscore the need for further research into the relationship between cognitive processing and rest-frame cueing design, and the resulting effectiveness in alleviating cybersickness in virtual environments.

**Keywords:** Cybersickness, Motion sickness, Rest-frame cueing, Cognition in virtual reality, Multi-modal interaction, Virtual reality, Mixed reality, Flight simulation, flight crew training

## INTRODUCTION

The integration of Virtual Reality (VR) into flight simulation not only presents an opportunity to revolutionize flight crew training from an economical point of view, compared to conventional flight simulation methods. However, it also introduces challenges, such as an increased occurrence of cybersickness, potentially undermining the effectiveness of VR-based training (Chang et al., 2020). To optimize the benefits of VR, addressing the heightened likelihood of cybersickness is crucial. The most widely accepted theory for cybersickness attributes its emergence to a sensory conflict between visual inputs from the virtual environment and the motion sensed by the vestibular system (Chang et al., 2020; Palmisano et al., 2020; Reason and Brand, 1977). The mitigation of this sensory conflict is considered an effective strategy for combating cybersickness.

A potential method to dissolve this sensory conflict is to introduce a visual reference to the actual environment in the virtual environment, for which the resulting visual inputs correspond to the motion that is sensed in the actual environment. The presentation of such a visual reference in virtual environments, also referred to rest-frame cueing, is as such hypothesized to be an mitigation method for cybersickness (NATO Science & Technology, 2021), although the effectiveness of rest-frames on cybersickness mitigation is dependent on the precise manner in which the rest frame is cued to the operator. An example of how rest-frame cueing for cybersickness mitigation is through mixed reality (MR), in which the virtual environment is visually blended with the actual environment, which has shown promising results for the mitigation of cybersickness (Englebert et al., 2023).

However, it has also been found that while MR reduces cybersickness, it also leads to a decline in pilot performance in virtual environment flight training, attributed to reduced immersion and lower simulation fidelity (Englebert et al., 2023). As an alternative, it is hypothesized that a visual grid in the virtual environment that is fixed to the orientation of the actual environment, also referred to as a Virtual Reference Grid (VRG), can be an effective alternative rest-frame cueing strategy that offers similar cybersickness reduction benefits as MR but may be more conducive to maintaining simulation fidelity. This study explores the effectiveness of a VRG as a form of rest-frame cueing on cybersickness mitigation, aiming to minimize cybersickness without compromising pilot performance.

The effectiveness of a VRG in helicopter flight simulation for cybersickness mitigation and pilot performance will be investigated by means of a human-in-the-loop experiment, incorporating multi-modal interaction with the real and virtual environments. It is expected that the participants will be able to cognitively process that the visual motion inputs from the VRG in the virtual environment correspond with the motion sensed in the actual environment, thereby diminishing the sensory conflict and alleviating feelings of cybersickness, while not breaking immersion to such an extent that it leads to pilot performance degradation.

## METHOD

In order to test the hypothesis that a VRG is effective for the mitigation of cybersickness in virtual environments, a human-in-the-loop experiment is carried out. This human-in-the-loop experiment featured a number of participants performing a set of flight maneuvers on a predefined parcours, while intermittently reporting their self-perceived level of cybersickness. This experiment task was performed in three conditions: (1) a baseline condition in which no rest-frame cueing is presented to the participant, also referred to as the No Visual Reference condition, (2) a condition in which a VRG is used as rest-frame cueing, known as the VRG Reference condition, and (3) a condition that features MR as a form rest-frame cueing. This is carried out in the same way as was done by Englebert et al. (2023), in order to compare this rest-frame cueing method to the VRG, called the MR Reference condition. This section describes the exact method that was employed for the human-in-the-loop experiment.

## Simulation Setup

For the human-in-the-loop experiment simulation setup, a simulated AgustaWestland AW139 helicopter flight model was utilized, coupled with low-fidelity helicopter flight controls and a Varjo XR-3 visual device to present the virtual environment. The Varjo XR-3, identified as an enhanced Mixed Reality device, boasts a high-resolution focus area (27° x 27°) and incorporates two RGB cameras for video input. The generation of the virtual environment was accomplished using Unity version 2020.3.4.

To ensure uniformity in each participant's experimental flight profile, a scenario encompassing multiple Mission Task Elements (MTE) from the ADS-33E-PRF (Baskett, 2000) was devised. Despite executing various MTEs during the scenario, particular attention was directed towards the ADS-33E-PRF pirouette MTE during results analysis, as it was deemed both the most visually dynamic and the most flight-technically challenging maneuver. In this task, the participants were instructed to navigate a circular trajectory while maintaining a consistent heading aligned with the center pole at specified distance and height. The scenario also incorporated a 15-knot wind in a fixed direction. An expectation is set that the dynamic, near-ground maneuvers in the pirouette MTE may heighten cybersickness more profoundly compared to stable tasks at higher altitudes. This anticipation is rooted in the likelihood of increased sensory conflict due to elevated vection levels (Lawson, 2014; Zelie and Qadeer, 2019). Figure 1 provides a visual representation of the pirouette MTE virtual parcours and flight task, and detailed specifications of the pirouette performance can be found in Table 1.

**Table 1.** ADS-33E pirouette MTE performance specifications (Baskett, 2000).

| Performance Specification | Desired Performance | Adequate Performance |
|---|---|---|
| Maintain distance to circle center (100 ft) | ± 10 ft | ± 15 ft |
| Maintain radar altitude / height (15 ft) | ± 3 ft | ± 10 ft |
| Complete full circle within | 45 seconds (~8 kts) | 60 seconds (~6 kts) |

## Cybersickness Measurements

Given the acknowledged variability in motion sickness susceptibility across individuals, participants in the experiment will undergo the Motion Sickness Susceptibility Questionnaire (MSSQ), designed by Golding (2006), before their involvement. This questionnaire aims to assess the diverse degrees of motion sickness susceptibility within the participant pool. The outcomes of the MSSQ will serve as a means to elucidate any irregularities or notable outliers observed in the cybersickness results. Additionally, participants will engage with the Misery Scale (MISC) following each trial. Ranging from 0 ("No problems") to 10 ("Vomiting"), the MISC provides a quantifiable measure of the discomfort experienced by participants during the experiment.

## Participants

Four helicopter pilots from the Royal Dutch Air Force were enlisted for the experiment, averaging 35.8 years in age (SD = 6.83 years) and accumulating an average flight experience of 1634 hours (min = 400, max = 4000). Among them, three pilots specialized in operating the Chinook, while one pilot possessed proficiency in both the AW139 and the NH90 helicopters.

To gauge the participant's susceptibility to cybersickness, the Motion Sickness Susceptibility Questionnaire (MSSQ) by Golding (2006) was administered prior to the experiment. The combined MSSQ score for the four participants averaged 8.75 (SD = 7.89). This positions the mean score within the 40th to 50th percentile range for motion sickness susceptibility, indicating a slightly lower susceptibility compared to the general population average (Golding, 2006). Consequently, it is deduced that they can partake in the experiment without significant concern for experiencing excessive sickness.

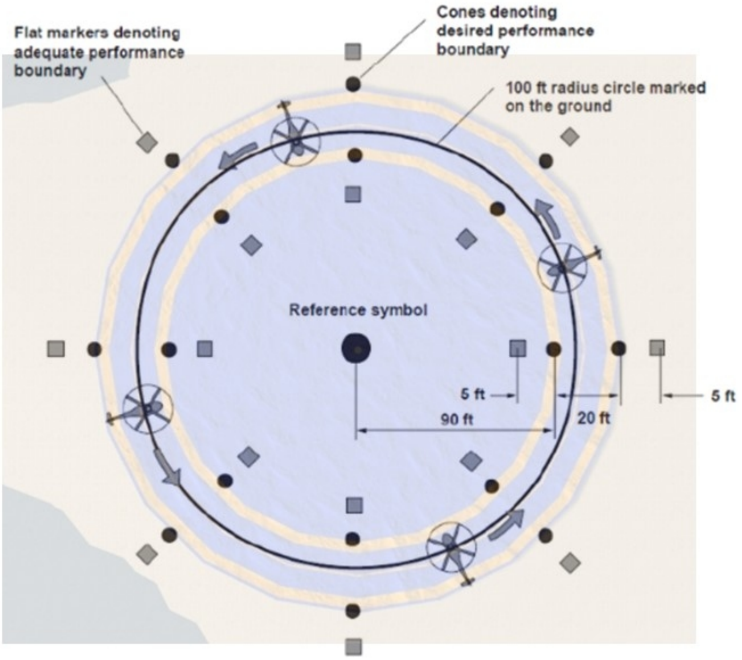


**Figure 1:** Combining the pirouette MTE procedures and performance limits outlined by Baskett (2000) with the virtual environment implementation of the pirouette MTE course.

## RESEARCH DESIGN

As discussed, three experiment conditions were devised to assess the influence of visual referencing utilizing MR and motion on cybersickness and flight performance: the No Visual Reference condition, the MR Reference condition, and the VRG Reference condition. A visual representation of these conditions in the virtual environment, showing the precise form of rest-frame cueing that was applied, is presented in Figure 2. From Figure 2a, it can clearly be seen that no visual artifacts related to the rest-frame are present in the No Visual Reference baseline condition, while Figure 2b shows the visual blending of the virtual and actual environments using an 80–20 transparency ratio that is used in the MR Reference condition, where the physical room in which the simulator is situated can be seen. Finally, Figure 2c shows the presence of a white visual grid as a VRG for rest-frame cueing, for which the orientation is fixed to the actual environment in which the simulator is situated, used in the VRG Reference condition.

Participants undergo all three experimental conditions within a single day, adhering to a predetermined counterbalanced order. Prior to commencement, participants receive instructions on utilizing the MISC (Bos and Patterson, 2006) and execute a familiarization run through the virtual environment in the No Visual Reference configuration. Following the familiarization run, participants rest until reporting a MISC score of 0, ensuring no carryover effects from the familiarization.

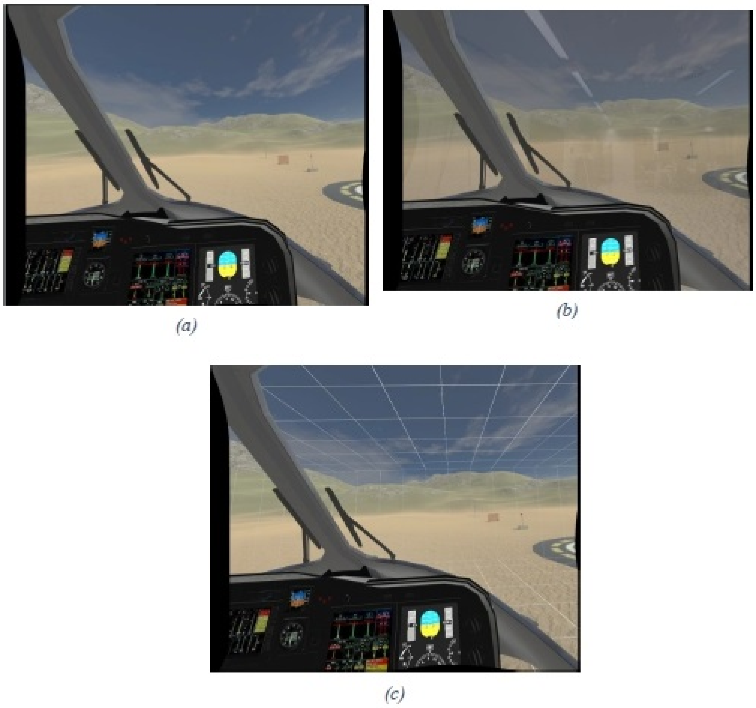


**Figure 2:** The participant's virtual cockpit eye reference point view for the three experiment conditions: (a) no visual reference, (b) MR reference, and (c) VRG reference.

Within each experimental condition, participants navigate the virtual course, encompassing all selected Mission Task Elements (MTEs), including the pirouette, performed twice to achieve a total scenario duration of approximately twenty minutes. This duration allows adequate time for the manifestation of cybersickness. Upon the completion of each MTE, the participants report their MISC score. In addition, the experiment condition was aborted when the participant reported a score of MISC 3, indicating mild cybersickness symptoms such as stomach awareness and dizziness, in order to prevent the excessive build-up of cybersickness that could prevent the participants from properly returning to a baseline level of cybersickness to execute the remaining experiment conditions on the experiment day. After completing a condition, the participants rested to recover from any cybersickness symptoms before initiating the next condition, contingent upon reporting a MISC score of 0, in order to prevent the cybersickness build-up from one condition affecting the development of cybersickness in the next condition.

### Dependent Measures and Data Analysis

Given the limited sample size and the exploratory nature of the experiment in this paper, no formal statistical analyses are undertaken. Nevertheless, various parameters are evaluated. Descriptive statistics and visual representations of cybersickness, specifically the MISC scores reported, are employed to scrutinize differences across conditions. Performance assessment involves the analysis of pertinent pirouette performance parameters, encompassing height deviation, distance deviation, and deviation from the heading corresponding to a specific position. Furthermore, flight trajectories for each condition are mapped and evaluated using the performance conditions outlined in Table 1.

## RESULTS

As described in the previous chapter, the results analysis features a descriptive assessment of both cybersickness and pilot performance measurements. The cybersickness and pilot performance results are presented in the next two sections.

### Cybersickness

Figure 3 visualizes the average MISC scores and standard errors that were reported after the completion of the pirouette MTEs ($n = 8$) for the three experiment conditions. Even though the average MISC scores and standard errors are comparable across the three conditions, it can be observed that the average MISC scores for the MR Reference condition appear to be slightly lower than for the baseline No Visual Reference condition, as was also reported by Englebert et al. (2023). However, from Figure 3 it is also apparent that this reduction in the average MISC score cannot be observed when comparing the VRG Reference and No Visual Reference conditions. In fact, the average of the MISC scores reported for the VRG Reference condition appears to be slightly higher than for the No Visual Reference condition.

Despite the fact the average MISC scores differ slightly across the experiment conditions, t-test paired samples statistical testing did not reveal any statistically significant differences for the MISC scores between the 'No

Visual Reference - MR Reference' ($t_7 = 1.53, p = 0.511$), 'No Visual Reference - VRG Reference' ($t_7 = -0.424, p = 1.00$), and 'MR Reference - VRG Reference' ($t_7 = 1.43, p = 0.591$) experiment condition pairs.

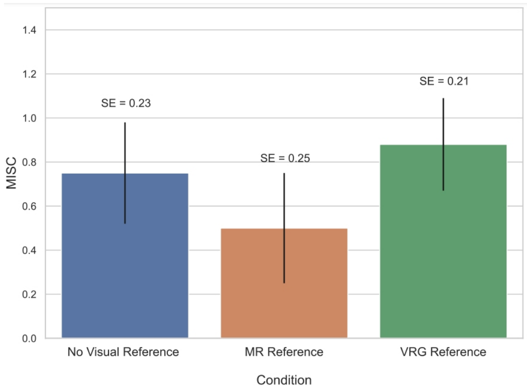


**Figure 3:** Average MISC scores and standard errors (SE) reported for the pirouette.

## Pilot Performance

In accordance with the performance metrics for the ADS-33 Pirouette MTE in Table 1, the pirouette MTE height, distance, and heading deviations for all available datapoints are presented in Figure 4 for the three experiment conditions. By comparing the height and distance deviations with the performance specifications laid out in Table 1, it can be noted that the pilots had difficulty with adhering to both the desired and adequate performance margins, for all three experiment conditions. The same can be said for the heading deviation, for which it is clear from Figure 3 that deviations in excess of five degrees are common, while a deviation of zero degrees is desired as the participants were instructed to keep the nose of the helicopter pointed to the center object in the pirouette MTE parcourse.

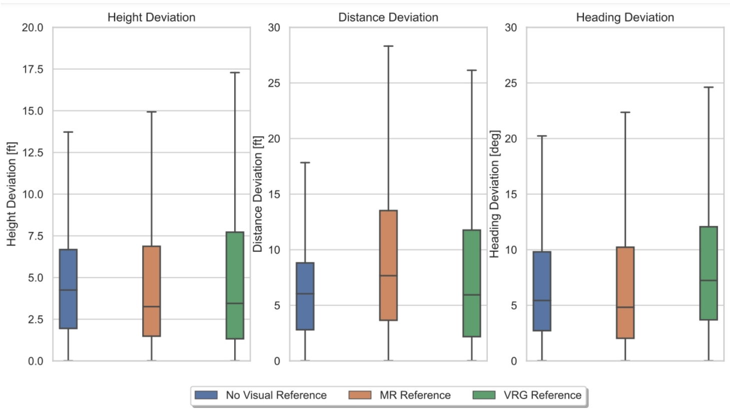


**Figure 4:** Pilot performance in terms of the height, distance, and heading deviation.

For the pilot performance in terms of the height and deviations, it can be argued that the deviations are comparable between the three experiment conditions, where only a minor increase in the heading deviations appears to be present for the VRG Reference condition, compared to the other two conditions. When it comes to the distance control, it can be observed from Figure 4 that the distance deviations are relatively high for the MR Reference and VRG Reference conditions compared to the No Visual Reference condition, where the MR Reference condition appears to more negatively impact the distance control pilot performance than the VRG Reference Condition.

The notion that the rest-frame conditions result in poorer pilot performance in terms of distance control compared to the No Visual Reference condition is also apparent when examining the flown pirouette MTE trajectories, which are visualized by means of a top-down view in Figure 4. To elaborate, a comparison between the flight trajectories in Figure 4 and the reference pirouette MTE trajectory shown in Figure 1 reveals that the flight trajectories for the No Visual Reference condition are not only more accurate with respect to the reference trajectory compared to the rest-frame conditions, but also that the variance of the distance to the pirouette center is higher for the rest-frame conditions than for the No Visual Reference condition. Between the two rest-frame conditions, it can be noted that the flight trajectories for the VRG Reference condition appear to be more accurate with respect to the reference trajectory than the MR Reference condition flight trajectories, highlighting that differences in distance perception and control do exist depending on the exact cueing of the rest frame.

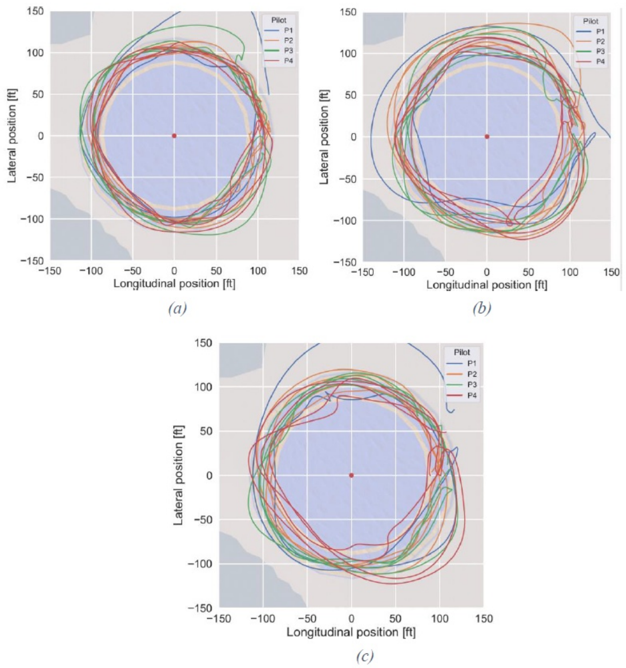


**Figure 5:** Pirouette MTE pilot flight trajectories for the three experiment conditions: (a) no visual reference, (b) MR reference, and (c) VRG reference.

## CONCLUSION

In order to assess the impact of a VRG as a form of rest-frame cueing on the development of cybersickness in VR helicopter flight simulation, a human-in-the-loop experiment was performed. While it had already been demonstrated that the use of MR rest-frame cueing can mitigate cybersickness (Englebert et al., 2023), the results from this human-in-the-loop experiment indicated that VRG rest-frame cueing does not have a mitigating effect on cybersickness, compared to the No Visual Reference baseline condition, in which no rest-frame cueing is presented. In terms of pilot performance, the results showed that the VRG rest-frame negatively affected distance and heading control in the pirouette MTE compared to the baseline condition. It was, however, also found the performance degradation for distance control in the VRG Reference condition was not as severe as in the MR Reference condition, indicating that a VRG rest-frame is potentially less detrimental for certain aspects of pilot performance than a MR rest-frame.

An explanation for these findings can be found in the remarks made by the participants after completion of the experiment. Three out of four participants reported that the VRG was interfering for the execution of the MTEs, that it did not provide any added value, and that attempts were made to ignore the VRG altogether. These remarks, in combination with the notion that the VRG did not have any beneficial effects for cybersickness mitigation, can be an indication that the participants did not understand that the VRG was fixed to the actual environment, and that the presence of the VRG only led to contrasting visual cues in the virtual environment. When it comes to pilot performance, the participants reported that the VRG rest-frame cueing did not impede on the visual perception of the virtual environment to the same extent as the MR rest-frame cueing, that effectively rendered the virtual environment less visible due to the blending with the actual environment. As such, they rated MR rest-frame cueing as more disruptive for task execution than VRG rest-frame cueing, despite MR rest-frame cueing resulting in a reduction of cybersickness severity.

The contrasting outcomes between the MR and the VRG types of rest-frame cueing prompt a deeper exploration of the role of cognitive processing of rest-frame cueing in cybersickness mitigation. Participants' lack of awareness regarding the fixed nature of the VRG as a rest frame to the actual environment raises questions about the effectiveness of this type of rest-frame cueing in providing a visual reference to the actual environment. The study suggests that the cognitive processing of the VRG was not sufficiently impactful in mitigating cybersickness. This conclusion highlights the importance of adequate rest-frame cueing design, to promote participants' understanding and cognitive awareness of rest-frame cues for effective cybersickness reduction for future research.

The study's findings underscore the critical role of effective design in rest-frame cues for cybersickness mitigation in VR. Designing cues that align with participants' cognitive processes and enhance their awareness of the virtual environment appears to be crucial. This consideration becomes even more pertinent as the VRG rest-frame, while not directly contributing to cybersickness mitigation, exhibits positive impacts on cognition and interaction. Researchers and designers should strive for a delicate and careful balance between cognitive benefits and cybersickness mitigation when crafting virtual environments.

## ACKNOWLEDGMENT

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