KTH ROYAL INSTITUTE
OF TECHNOLOGY

Degree Project in the Field of Technology and the Main Field of Study Computer Science and Engineering

Second cycle, 30 credits

Cybersickness in a Virtual and Mixed Reality Flight Simulator With a Video See-Through Head-Mounted Display

CHRISTIAN K. K. LINDBERG

Stockholm, Sweden, 2023

Cybersickness in a Virtual and Mixed Reality Flight Simulator With a Video See-Through Head-Mounted Display

CHRISTIAN K. K. LINDBERG

Master's Programme, Interactive Media Technology, 120 credits
Date: October 17, 2023

Supervisors: Björn Thuresson, Rogier Woltjer
Examiner: Tino Weinkauf
School of Electrical Engineering and Computer Science
Host company: FOI: Swedish Defence Research Agency
Swedish title: Cybersjuka i en Virtuell- och Blandad-Verklighet Flygsimulator Med en Huvudmonterad Bildskärm Med Kamera-Genomseende

Cybersickness in a Virtual and Mixed Reality Flight Simulator With a Video See-Through Head-Mounted Display

CHRISTIAN K. K. LINDBERG

The Swedish Air Force Combat Simulation Centre (FLSC) is investigating how immersive technologies can be used with flight simulators. Cybersickness is sickness-like effects experienced when immersed in virtual environments using head-mounted displays. Research suggests that cybersickness is less severe in Mixed Reality (MR), where the environment is mixed with virtual and real objects, when using an optical see-through head-mounted display. The primary objective of this thesis was to determine differences in cybersickness in a Virtual Reality (VR) and MR flight simulator when using a video see-through head-mounted display. Twenty-nine volunteers participated in a cross-over experiment with repeated measure design, at FLSC in Kista. Cybersickness was assessed using the Simulator Sickness Questionnaire (SSQ) and Fast Motion Sickness scale (FMS). Results showed that the mean total score of SSQ was higher in VR (M = 15.6) than MR (M = 12.6) although not statistically significant (p = .44). The mean FMS was also higher in VR (M = 1.34) than MR (M = 0.83) at a significant level (p = .035). Subscale scores of the SSQ showed that disorientation symptoms had a higher mean in both VR and MR, compared to nausea and oculomotor discomfort symptoms. Only in MR was disorientation symptoms significantly higher than nausea (p = .011). The thesis concluded that cybersickness seems less severe in MR and that disorientation symptoms seems predominant in MR and VR.

SAMMANFATTNING

Flygvapnets Luftstridssimuleringscentrum (FLSC) undersöker hur immersiva teknologier kan användas vid flygsimulering. Cybersjuka är sjukdomsliknande effekter som upplevs i virtuella miljöer med huvudmonterade bildskärmar. Forskning tyder på att cybersjuka är mildare i en "blandad verklighet" (MR), där miljön är blandad med virtuella och verkliga objekt, när man använder huvudmonterade bildskärmar med optik-genomseende. Det primära syftet med detta examensarbete var att fastställa skillnader i cybersjuka mellan en helt virtuell verklighet (VR) och MR-flygsimulator när man använder en huvudmonterad bildskärm med kamera-genomseende. Tjugonio frivilliga deltog i en överkorsningsprövning med upprepad mätning, vid FLSC i Kista. Cybersjuka utvärderades med Simulator Sickness Questionnaire (SSQ) och Fast Motion Sickness scale (FMS). Resultaten visade att medelvärdet för totalpoängen för SSQ var högre i VR (M = 15.6) än MR (M = 12.6) men inte statistiskt signifikant (p = .44). Medelvärdet för FMS var också högre i VR (M = 1.34) än MR (M = 0.83) och statistiskt signifikant (p = .035). Subskalepoäng för SSQ visade att desorienteringssymptom hade högre medelvärden i både VR och MR, jämfört med illamående och ögonbesvär. Endast i MR var desorienteringssymptom signifikant högre än illamående (p = .011). Uppsatsen drog slutsatsen att cybersjuka verkar lindrigare i MR och att desorienteringssymptom verkar dominerande i MR och VR.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; **Mixed / augmented reality**.

Keywords: cybersickness, virtual reality, mixed reality, flight simulator, military

Nyckelord: cybersjuka, virtuell verklighet, blandad verklighet, flygsimulator, militär

Author's address: Christian K. K. Lindberg, ckkli@kth.se, KTH Royal Institute of Technology, School of Electrical Engineering and Computer Science, Stockholm, Sweden, SE 100 44.

Document date: October 17, 2023

Swedish title: Cybersjuka i en Virtuell- och Blandad-Verklighet Flygsimulator Med en Huvudmonterad Bildskärm Med Kamera-Genomseende

ACRONYMS

AR Augmented Reality. 3, 4, 10, 30
AV Augmented Virtuality. 4, 5

CS Cybersickness. 3–5, 7–20, 22, 24, 26, 27, 29–32

FLSC Swedish Air Force Combat Simulation Centre. 3, 4, 10, 16, 19, 31
FMS Fast Motion Sickness scale. 13, 14, 16, 19–22, 25–27, 29–31
FOI Swedish Defense Research Agency. 3, 20
FPS Frames Per Second. 9

HDD Head-Down Display. 19
HMD Head-Mounted Display. 3–5, 8–11, 13, 20, 21, 29, 30, 32

MISC MIsery SCale. 14, 16
MR Mixed Reality. 3, 4, 30, 32
MS Motion Sickness. 5–9, 11, 12, 15
MSSQ Motion Sickness Susceptibility Questionnaire. 15, 20–22, 26

OST Optical See-Through. 3, 5, 9, 10, 30, 32

RE Real Environment. 4

SS Simulator Sickness. 3, 5–8, 10, 11
SSQ Simulator Sickness Questionnaire. 9, 10, 12–14, 16, 20–22, 24–26, 29–31

VE Virtual Environment. 4
VIMS Visually Induced Motion Sickness. 5, 7, 10
VR Virtual Reality. 3, 4, 32
VST Video See-Through. 3, 5, 9, 10, 18, 20, 29–32

WSRT Wilcoxon Signed Rank Test. 22, 24–26

XR eXtended Reality. 3, 4, 13, 31, 32

1 INTRODUCTION

In the late 1950s, early military flight simulators were inducing pilots to experience sickness effects. This Simulator Sickness (SS) was a chief reason for discontinuing the use of some flight simulators [24]. Research and development have helped mitigate the SS after that but the issue still remains [27]. Today, simulators and applications in virtual environments face a similar issue, referred to as Cybersickness (CS), when experienced through eXtended Reality (XR) headsets [27, 37, 44, 51]. XR is an umbrella term for all technologies that extend the reality we experience which include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) – this is done by either merging a virtual world with the real world or by creating a fully virtual experience [43].

The Swedish Air Force Combat Simulation Centre (FLSC), a department at the Swedish Defense Research Agency (FOI), develops and hosts a world-leading flight combat simulation facility since 1998 [17]. Currently, their simulators project the virtual environment onto large domes surrounding the pilots or display it on simple computer screens. However, FLSC is evaluating how novel immersive technologies should be utilized in their facility and evaluating the potential development of an XR flight simulator. One specific key technology to evaluate is Head-Mounted Display (HMD), used to display virtual environments in stereoscopy, e.g., headsets like Meta Quest 2 [58] or Varjo XR-3 [57].

There are many potential benefits and limitations for training pilots in an XR flight simulator but one often-reported limitation is the occurrence of sickness effects [12]. Severe sickness can have negative effects on a pilot's training, in terms of directly reducing user performance [42], but also in discouraging the pilots from using the flight simulator [14, 44]. Therefore, the expected severity of CS and ways of mitigating it should be investigated.

Novel XR HMD offers the ability to create a simulator with varying amounts of virtual objects. With this a question arises as to whether different degrees of virtuality elicit different degrees of CS. Would one degree of virtuality elicit less CS? Previous research has indicated that Optical See-Through (OST) AR HMD *can* elicit severe CS [26], but that it generally seems to elicit less severe CS the less virtual the environment is [27, 35]. Previous research has also indicated that the symptoms are different between VR and AR, with eye strain symptoms being more prominent in AR [23, 56] and disorientation being more prominent in VR [23, 50]. An OST HMD allows real-world photons to pass through a transparent display, to which a virtual environment can be overlaid, into our eyes, while a Video See-Through (VST) HMD captures the real-world photons via cameras and displays a software-merged MR on non-transparent displays. However, there is a gap on the differences in CS with VST HMDs [35, 44].

1.1 Objectives

The main objective of this study is to determine any differences in elicited CS between a VR and MR flight simulator using a VST HMD. The following research question is to be answered:

RQ: *How does cybersickness compare between a VR and MR flight simulator, using a video see-through XR head mounted display?*

Research indicates that OST HMD seem to elicit less severe CS the less virtual an environment is [26, 27, 35] – and that the cardinal symptoms in AR and VR respectively relate to eye strain and disorientation [23, 50, 56]. Thus, the following hypotheses are formed:

H1*: the severity of cybersickness will be less severe in the MR flight simulator compared to the VR flight simulator.*

H2*: Oculomotor (eye strain) symptoms will be predominant in the MR flight simulator.*

H3*: Disorientation symptoms will be predominant in the VR flight simulator.*

In addition, this study also aims to (i) provide an overview of CS, (ii) prototype a XR flight simulator using the Unreal Engine platform, (iii) test a method of measuring physiological data and correlate it with CS, and (iv) indicate how severe CS the simulator users at FLSC could expect from a XR flight simulator.

1.2 Limitations and Significance of the Study

The population of interest is air force pilots, who are not readily available subjects. The study will be limited by using subjects that are not necessarily pilots.

The results of this study may inform FLSC as to which degree of virtuality is preferable in an XR flight simulator concerning CS. The results may also help the research field in understanding how various levels of virtuality affect CS.

1.3 Delimitations

The flight simulator to be prototyped will have to be delimited in several regards. A 'real' combat flight simulator would be out of scope for this project. Delimitations will be in terms of realism and fidelity. Graphics and functions such as interactable interfaces in the cockpit will be restricted, meaning that the stimuli may not be fully representative of what is used in fighter pilot simulator training environments. This study will also delimit its investigation of what factors are affecting CS. The focus is to answer *how* CS changes and not *why*.

2 BACKGROUND

The background introduces eXtended Reality (XR) flight simulation, defines vague terms and concepts, provides an overview of history and theories concerning CS, and related work.

2.1 Extended Reality Flight Simulation

XR is getting more popular and has been shown, and speculated, to be beneficial in several domains, e.g., education [1] and medicine [2], improving the ways we consume information, communicate, and work. One of these domains is flight simulators for pilot training. A recent literature review [12] detailed several reported benefits and limitations of a flight simulator using XR technology. Some of the most-reported benefits included reduced costs, increased flexibility, increased immersion and realism, and the possibilities of strengthening and improving users' cognitive ability, attention, spatial and peripheral awareness. While the most reported limitations included degradation of user performance (due to technical limitations of many HMD, e.g., low field of view and pixel resolution), limited usability of interactions with virtual controls in VR (due to, e.g., poor hand tracking), increased physical workload and fatigue (due to XR equipment, e.g., wearing a heavy HMD), and the issue of CS.

Many of the limitations are technical in nature, which suggests they may be handled by further advancements in technology. On the other hand, CS is highly related to human factors which may be harder to handle. When CS became a well-known issue during the VR hype in the 1990s, some assumed that technology would solve many of the problems causing CS [37]. But the issue is still largely unsolved and may hinder the adoption of XR technology.

2.2 Definitions and Terminology

2.2.1 The virtuality continuum — XR, AR, AV, VR, MR. This study follows the often-cited definition of the virtuality continuum outlined by Milgram and Kishino [43], illustrated in Figure 1. They posed the Real Environment (RE) and Virtual Environment (VE) on the two ends of this continuum. Augmented Reality (AR) is defined as a predominantly Real Environment (RE) augmented with virtual objects and, vice versa, Augmented Virtuality (AV) is defined as a predominantly Virtual Environment (VE) augmented with real objects. Virtual Reality (VR) is then defined as a completely synthetic world that a person is immersed in – and Mixed Reality (MR) is anywhere between the two ends of the continuum, with Real Environment and Virtual Environment presented together. Milgram and Kishino did not define eXtended Reality (XR), but it is a commonly used umbrella term referring to this whole virtuality continuum [59], including any current and future technologies.

However, when referring to previous works, this study will use whatever term the original authors used.

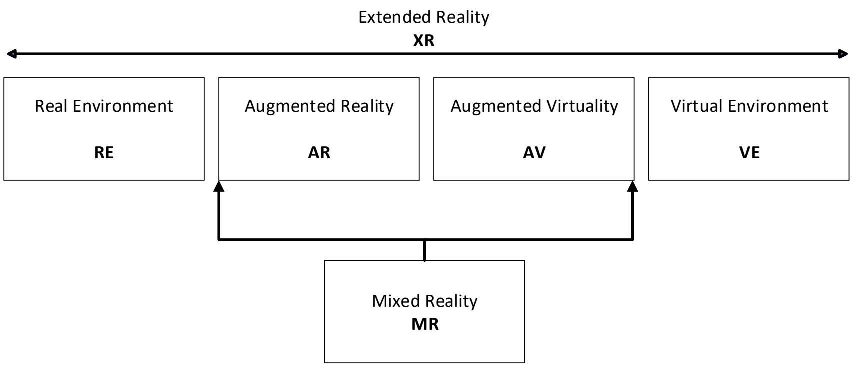


Figure 1: The virtuality continuum. Adapted from [43].

2.2.2 Head mounted displays. A Head-Mounted Display (HMD) is a device, most often, with two screens, one in front of each eye, supplying a stereoscopic view of virtual environments. A VR HMD often occludes the whole real environment to immerse the user in total VR. In AR HMD the real environment is visible with virtual environment overlaid on Optical See-Through (OST) displays. I.e., virtual environments projected on a transparent piece of glass-like goggles. A MR/XR HMD should per definition be able to span the virtuality continuum more freely, being able to also create AV experiences. Currently this technology relies on Video See-Through (VST) display, meaning the screen streams the real environment via cameras on the HMD.

Highlighting the ambiguity of the virtuality terms is the advertised capabilities of head-mounted displays – in what virtuality degree they can create. E.g., the Microsoft HoloLens 2 is said to be able to create MR, but per the definition in the above section it cannot create AV since the low field of view (60°) reveals a lot of the real environment. More accurately, HoloLens 2 would be called an AR HMD. An example of an HMD that can create MR is the Varjo XR-3, by using VST technology. Figure 2 shows the two HMD.

2.2.3 Motion sickness. In literature, Motion Sickness (MS) is the general term for many similar sickness effects. The medical term for MS is kinetosis and is not a true sickness/disease, but a normal response from a healthy individual, perhaps more properly sometimes referred to as motion maladaptation syndrome [24]. There are several subtypes of MS, including Cybersickness, which can be differentiated from other subtypes as shown in Figure 3. There is no clear boundary between the many types and overlap exist.

What distinguishes the different subtypes are mostly the type of environment they occur in and their symptomology (i.e., their most frequent symptoms). Transportation sickness, e.g., car sickness and sea sickness, are primarily caused by physical motion with nausea and dizziness being the cardinal symptoms and is shown by signs of pallor, sweating, and vomiting [24, 27]. Which is contrast to simulator sickness, and its subtypes, that are primarily caused by visual stimuli and often include symptoms of eye strain.

2.2.4 Simulator sickness. As its name suggests, Simulator Sickness (SS) was coined in the early days of flight simulators in the 1950-60s. SS and its subsets, CS and VIMS (as shown in Figure 3) are poorly distinguished in the literature. E.g., one paper described SS as caused by visual motion not requiring physical motion, only a wide field of view display [24]. However, more recent literature described SS as caused by discrepancies between a visual stimulus,

(a) Microsoft HoloLens 2, an Augmented Reality Optically See-Through head-mounted display (public domain Wikimedia Commons [49])

(b) Varjo XR-3, an eXtended Reality Video See-Through head-mounted display (free use © Varjo)

Figure 2: Examples of an Optically See-Through (a) and Video See-Through (b) head-mounted display

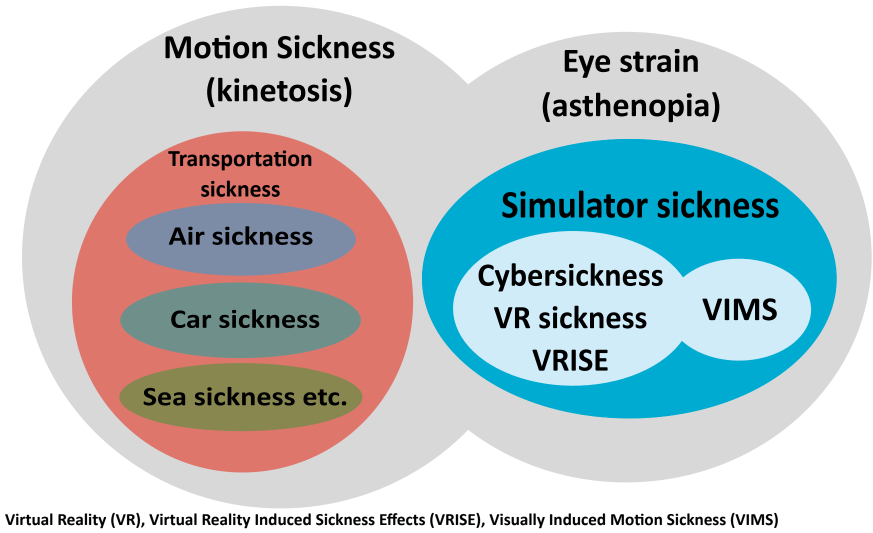


Figure 3: Hierarchical outline of motion sickness taxonomy. Colors and sizes are for clarity. Sicknesses inside "motion sickness" mainly results from physical motion, while in "eye strain" is due to visual stimuli. They can overlap, such as getting eye strain with car sickness or getting motion sick by visual motion stimuli. Adapted from Figure 1 in [4] and Figure 2-2 in [6].

indicating motion, and the physical motion of a moving platform [6, 14]. This is the definition followed by this study. The cardinal symptoms of SS are similar to those of MS, with the difference of less gastrointestinal distress (e.g., stomach awareness, nausea, vomiting) and the inclusion of oculomotor symptoms (e.g., eye strain, blurred vision, headache) [6, 14, 24]. SS is reported as less severe and occurring less frequently than MS [14].

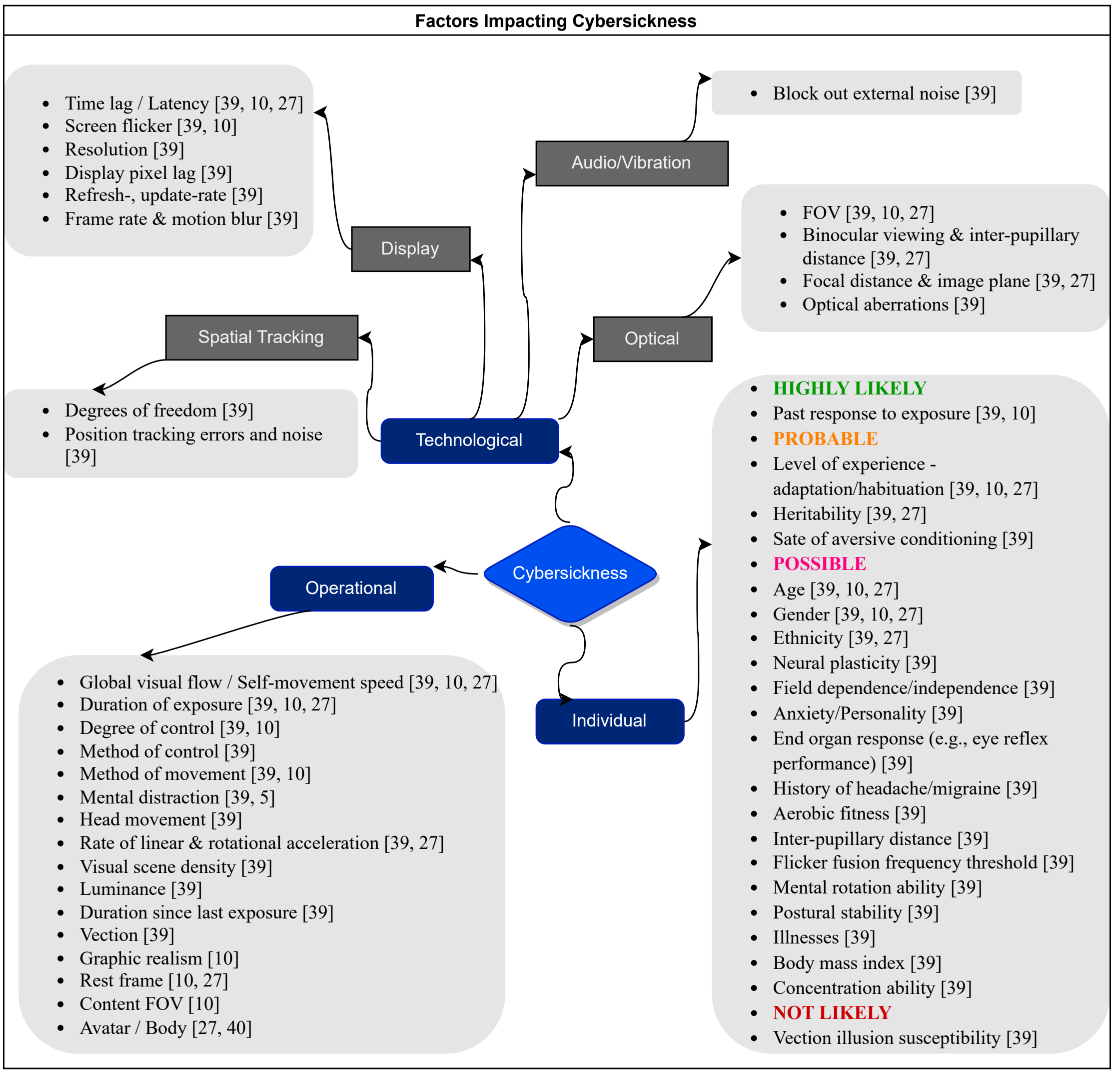


Figure 4: Mindmap of several factors likely influencing cybersickness. With references [5, 10, 27, 39, 40] showing where they are discussed. The likelihood-rating of the individual factors are from Lawson et al. [39].

2.2.5 Visually induced motion sickness & Cybersickness. Visually Induced Motion Sickness (VIMS) is caused by visually perceived motion, regardless of being digital or real visual stimuli [28]. CS is not definitively defined in the literature. It has been defined as VIMS caused by any digitally driven display [6], while some refer to it as VR sickness or virtual reality induced sickness effects (VRISE) [27], indicating that it should be regarded as caused from VR experiences. However, those names suggest one is only referring to one level on the virtuality continuum.

Furthermore, the terms CS and SS also seem to be used interchangeably in some literature (e.g., [27]), causing confusion. Hence, for the sake of clarity, this study follows the definition stated by Kirollos et al. [35], that CS is a variation of SS (which is a variation of MS) elicited from the use of XR HMD. The cardinal symptoms of CS include nausea, eye strain and dizziness and has been reported as being more severe than SS [14].

2.3 Factors of Cybersickness

Even though there might be no consensus on why CS occurs, there are a vast number of known factors that can influence CS, as shown in Figure 4. This section will present many factors impacting CS found in the pre-study but should not be seen as exhaustive. The factors are divided into three categories: individual, technological, and operational.

2.3.1 Individual factors. As seen in Figure 4, factors in this category are rated on its likelihood to affect CS. The rating follows the statements made by [5], who reviewed a large number of literature, listed possible factors, and conservatively rated them based on available evidence. The most reliable factor was arguably 'past response to exposure' (described further in Section 3.4.4). Another well-known fact is that a person can adapt to exposures – by exerting oneself to a stimulus the brain adapts to the stimuli and, following the sensory conflict theory, learns what kind of sensory information to expect. Lastly, an important note is that some individuals always seem to experience CS while some never do [27], as illustrated in Figure 5.

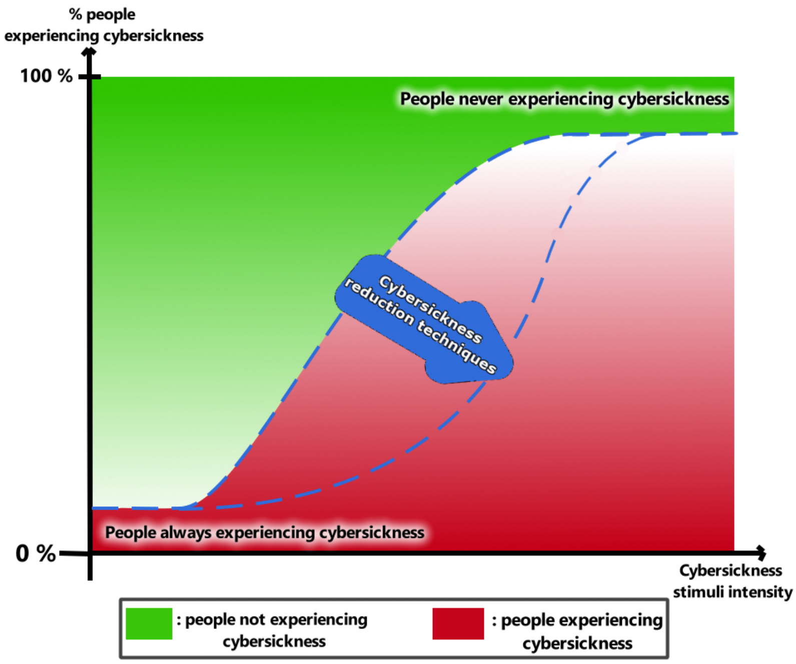


Figure 5: Diagram illustrating individual susceptibility for cybersickness and how some may always experience it while others may never. Adapted from Figure 4.7 in [27].

2.3.2 Technological factors. The technological factors are further categorized into spatial tracking, display, optical, and audio. One of the more critical factors is time lags/latency across the technology pipeline. An increase in time lags increases the severity of CS [10, 27, 39]. An often-mentioned term for the lag across the whole chain of technologies is motion-to-photon lag. As illustrated in Figure 6, it begins with the user's action, specifically head/body motion, and ends with the visual result entering the eye. The human eye has autonomous reflexes to stabilize the gaze as the head/body moves, called vestibulo-ocular reflexes, which has a response time of less than 10 ms [27]. The motion-to-photon lag of a system would thus have to match this level to avoid perceptual conflicts. E.g., just the content rendering stage would have to be at 100 Frames Per Second (FPS) to render a frame at 10 ms, meaning the FPS should be more than 100 for the motion-to-photon lag to not exceed 10 ms.

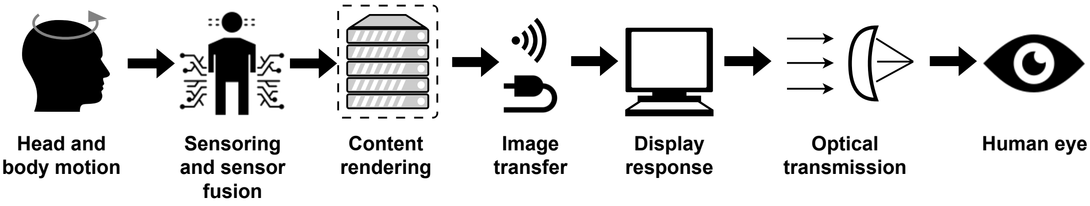


Figure 6: Motion-To-Photon pipeline. Several steps in a system add up to the final lag/latency experienced by a user. Adapted from Figure 5-2 in [39].

2.3.3 Operational factors. Operational factors encompass the content of the application, how the user can interact, and what the user does. Important factors in our study are degree of control, global visual flow, rest frame, mental distraction, and avatar/body perception.

Research has shown that predictable motion is less provocative, that having control of a vehicle and the movement of it induces less CS [10, 39]. The higher degree of control the user has the better. Likewise, when the user is stationary, less CS is elicited and when movement occurs and the visual flow increases, the CS increases. This has been thought of as the result of vection – the sense of self-motion – that the more a user feels like they are moving the more CS is elicited. However, [39] believed that the evidence for this is questionable and argued that it is simply the visual flow that is the factor, rather than the sensation of self-motion. Furthermore, rest frames (as described in Section 3.2.4) are regarded as helping mitigate CS. In a VR flight simulator there are two common rest frames: the background reference frame of a horizon and the foreground reference frame of the cockpit. In MR the real environment could also be acting as an earth-fixed reference frame – depending on how much of the real environment is visible.

Regarding the *duration of exposure*, it is said that CS can be elicited within a few minutes and the severity increases with time [10, 39]. *Mental distraction* says that performing a cognitive task during motion exposure can lower MS [5]. Lastly, *avatar/body* perception pertains to the ability to see one's own body or a virtual representation of one's body (an avatar) in the XR experience. This relates to the concept of sense of embodiment, meaning the illusory sensation that the body seen belongs to the user and that the body is present in the virtual environment. Kemeny et al. [27] and Leoncini et al. [40] point out that the link between the sense of embodiment and CS is unclear but state that it makes sense that not seeing one's body would create conflicts with the proprioceptive system and affect spatial orientation and, thus, lead to sickness effects.

2.4 Related Work

It is important to emphasize that drawing inferences on previous research and characterizing CS symptoms is challenging as several factors are at play. When it comes to Mixed Reality Head-Mounted Display (HMD) an important technology to distinguish between is Optical See-Through (OST) and Video See-Through (VST), as the underlying factors may change significantly between the two.

2.4.1 Defining symptom profiles. The Simulator Sickness Questionnaire (SSQ) is a self-report instrument used in the majority of research to measure CS (described further in Section 3.4.1. It gives a total score (TS) and three subscale scores which are related to symptoms of nausea (N), oculumotor discomfort (O), and disorientation (D). These subscale scores have been used to build symptom profiles (N vs. O vs. D) to characterize an exposure.

2.4.2 CS characteristics in Virtual Reality and Augmented Reality. A lot of research has been reporting on SSQ measurements of VR applications, showing that disorientation is dominant. In 1997, [52] pointed out that CS seem to have an SSQ symptom profile of D>N>O with a higher SSQ-TS compared to Simulator Sickness, averaging above 20. More recently, in 2020, a systematic review [50] found the average symptom profile to be D>O>N (means around 23.5 > 17.1 > 16.7) across 55 studies with an average SSQ-TS ranging from 14.3 to 35.3.

However, less research has been done on characterizing different levels of MR but, research suggests that oculomotor discomfort is dominant with OST AR HMD and hand-held tablets. In 2020, Hughes et al. [23] investigated how CS is characterized in AR, experimentally comparing CS between a Hololens 1 and a 10.5" tablet. Measured five times during an hour of exposure, the SSQ-TS mean were 15-25 with the HMD and 5-17 with the tablet, also suggesting a symptom profile of O>D>N for both devices. In 2022, Kaufeld et al. [26] investigated wether Visually Induced Motion Sickness can occur with OST AR HMD in two experiments exerting subjects with two different AR exposures using the Microsoft HoloLens 1 and HoloLens 2. A SSQ-TS mean of 13 and 40 showed that severe VIMS (following the benchmark of [29]) can be elicited in AR with these HMD. The experiments also suggested a symptom profile of O>D>N. Van Benthem et al. [56] conducted a literature review and found that, with OST AR HMD, the CS levels were consistently low with the SSQ-TS ranging from 0 to 20 and oculomotor discomfort being the dominant symptom category in general.

2.4.3 CS characteristics in Mixed Reality towards Augmented Virtuality. A previous master thesis at FLSC by Dahlkvist [13] investigated usability, presence, and CS in two degrees of virtuality. A VR and MR flight simulator where the cockpit, main interfaces, and user's body was real environment, using a Varjo XR-3 VST HMD. The CS was measured in a self-report questionnaire, asking 'how do you feel?' on a 7-point Likert scale (0 = good, 6 = sick). Subtracting a baseline average the post-exposure result showed a mean of 0.19 (VR) and 0.28 (MR). Similarly, Laudien et al. [36] investigated several aspects of a flying taxi simulator in four degrees of virtuality (one VR & three MR) using a Varjo XR-3 VST HMD, with CS also being measured. As CS was not the focus of the study, only descriptive results of CS were presented for two blocks evaluating all versions (i.e, not grouped by VR vs. MR), with a median SSQ-TS of 6.5 when the taxi was stationary and 18.7 when the taxi was flying hands-off.

The findings of [13] and [36] suggests that our study, which has a similar setup, could expect little to no difference in CS between any virtuality as long as the subject has control of the aircraft's movement. However, with limitations such as only measuring in one dimension; potentially missing symptoms, and with the results not being statistically analyzed, conclusions cannot be drawn. It is therefore worthwhile to investigate any differences in CS between a MR and VR flight simulation more thoroughly.

Focusing on comparing CS in two levels of MR, Kirollos et al. [35] used an office environment: one with a higher degree of virtuality (MR+) and one lower (MR-). Displayed using the OST HMD HoloLens 2, subjects were tasked with turning their head, in the yaw-axis, from shoulder to shoulder following a metronome rhythm during five 5-min blocks. The results showed that the SSQ-TS increased over time in both conditions, reaching a significantly different mean TS of 11.6 (MR-) and 27.0 (MR+) around 25 min. The subscale scores of the SSQ showed a symptom profile of D>O>N but did not reach statistical significance.

The findings of [35] suggests that less virtual environment in MR correlate with less CS and that CS increases over time if enough virtual environments are displayed. Their symptom profile of D>O>N also contradicts other reports (in Section 2.4.2) that suggests OST HMD elicit symptom profiles of O>D>N. However, all these findings might not be transferable to a VST MR HMD with VST technology.

3 EXTENDED BACKGROUND

This section details more about CS including history, theories, known symptoms and relevant measurements of CS.

3.1 A Brief History of Cybersickness

Research on CS builds upon research on SS and MS. MS was known and documented way back in ancient Greece, and have been scientifically researched since at least the late 19th century [24, 27]. SS has been researched since at least the 1950s, stemming from the early days of digital flight simulators [24, 27]. Some early examples of known CS from VR HMD were VR arcade machines in the early 1990s and Nintendo's Virtual Boy in 1995 [45]. The Virtual Boy was a commercial failure that could at least be partially attributed to the CS people got from it [15]. Research on CS has also been conducted since at least the 1990s, e.g., well-known researchers in the field published a paper in 1997 arguing that symptoms of CS are distinct from SS [53]. In 2013 came the VR HMD 'Oculus Rift Development Kit One' that can be considered as the start of the modern era VR boom [45]. Compared to MS, CS can therefore be considered relatively new, especially when concerned with MR HMD which is even more novel than VR HMD.

3.2 Theories of Cybersickness

Currently, there is no universally accepted theory or solution that fully explains and mitigates CS. There are three often-mentioned theories in the literature, with consensus being that the 'Sensory Conflict theory' is the most accepted currently [14]. These theories were developed to explain MS but is in the literature considered to explain all its subsets as well to a large degree, including CS.

3.2.1 Evolutionary theory. The *evolutionary theory*, also called the poison theory, as outlined by Treisman in 1977 [55], states that MS is a sort of biological survival mechanism. Coming in to play when experiencing sensory hallucinations similar to having ingested some type of poison. Becoming nauseous and vomiting is thus meant to eject the poison. However, the theory fails to explain several things such as why there is a great number of other symptoms, why not all people have a vomiting reaction, and the fact that the time needed for a toxin to spread through the body to affect our senses seem too long for vomiting to be effective [14, 27]. This theory has been given the least recognition in the literature [14].

3.2.2 Ecological theory. The *ecological theory*, also called postural instability[1] theory, as outlined by Riccio and Brand in 1991 [48], states that we become sick as a result of not having (or having not yet learned) effective control of our postural stability in an environment that changes abruptly. The longer the instability, the more severe symptoms. The human body has several sensory signals that trigger balance functions, such as visual, auditory, proprioceptive, and vestibular sensors. In a virtual environment with only visual changes, these body balance functions may not function properly and fail to keep postural stability [27]. However, the theory fails to explain several facts, such as how people with damaged inner ears, with defective sense of head orientation, very often do not suffer from MS while still showing postural instability [6]. There is also ambiguity as to how postural instability and MS are (cor)related (positively or negatively) [6].

3.2.3 Sensory conflict theory. The *sensory conflict*, or sensory rearrangement, theory as outlined by Reason and Brand in 1975 [47], is the most cited, with 1836 citations on Google Scholar, and is regarded as the most widely accepted theory in the literature [14]. It suggests that MS is caused by mismatch between the current sensory information and what the brain expected based on previous experience. However, as with the other theories, this theory fails to explain

[1]Postural instability – meaning one's body not being stable in upright position

why certain individuals get MS and others do not, given an identical stimulus [14]. It also fails to explain why there exist cases that can lead to sensory conflicts without inducing MS [48].

There are three sensory systems mainly involved in CS, according to [27]: (i) the vestibular system with organs in the inner ear consisting of the otoliths that sense linear accelerations and inclinations, and semicircular channels that sense angular accelerations; (ii) the visual system of our eyes giving clues on body and objects positions in space; and (iii) the proprioceptive system with receptors throughout the body that sense joint positions, movement and force on the body. Signals from these systems are transmitted and integrated in the brain to create an overall representation of body position, orientation, movement, and acceleration. The visuo-vestibular conflict is generally said to have the most impact on CS [6]. That is, the eyes perceive motion, but the vestibular system indicates no motion.

3.2.4 Rest frames. In addition to the three theories above, a fourth theory sometimes mentioned is the *rest frame theory* formulated by Prothero in 1998 [46], though it is open for discussion whether it should be considered a distinctive theory or a refinement of the sensory conflict theory [27]. The theory states that CS is the result from conflicting rest frames caused by motion cues. A rest frame is a stationary reference for which to define and compare spatial positions and motions of an object against. The brain measures relative motions between a stationary reference (the rest frame) and a nonstationary reference. Thus, when the brain fails to select an appropriate rest frame a conflict occurs causing sickness.

Three types of rest frames are often-mentioned in the literature: foreground, background, and earth-fixed rest frame. A reason why AR seems to elicit less CS could be the result of seeing more of the real world and providing the brain a clear earth-fixed rest frame [27].

3.3 Symptoms of Cybersickness

A detailed review of symptoms was done by Bos and Lawson [5] in 2021. Having reviewed literature, they reported on a total of 34 symptoms, of which 24 were identified as “well-established” in the sense of being included in the most often-used rating scales in the field (see Appendix A.1). These symptoms can be grouped in several ways according to Bos and Lawson. Some symptoms can only be judged by introspection[2], e.g., lack of motivation or fullness of head, and these psychological symptoms are thus highly subjective. Furthermore, some symptoms can be observed through behavior or physiological responses, e.g., sweating or pallor, and are thus more objective. However, Bos and Lawson also stated that some symptoms do not appear to have a clear dominance towards either distinction, such as nausea – which is both psychological and neurophysiological. A symptom can also start as a psychological effect and end with a neurophysiological reflex.

Bos and Lawson [5] further pose that, on average, some symptoms appear earlier than others and that this implies three major progression categories: pre-nausea, nausea, and retching[3]/vomiting – with a reservation that retching/vomiting can occur without nausea. The pre-nausea symptoms include dizziness, pallor, feelings of warmth, headache, stomach awareness, difficulty concentrating, and increased salivation, but differ between people.

3.4 Measurements of Cybersickness

3.4.1 Simulator sickness questionnaire (SSQ). The most well-known, used, and cited self-report questionnaire is the Simulator Sickness Questionnaire (SSQ) developed and validated by Kennedy et al. [29]. It consists of 16 items, representing several symptoms, rated on a four-point Likert scale (0 = “none”, 1 = “slight”, 2 = “moderate”, 3 =

[2]Introspection - that is, the examination of one’s own conscious thoughts and feelings, measured through self-reports.
[3]Retching - that is, the stomach movement of vomiting, without actually throwing up.

"severe"). The items are classified into three subscales: *Oculomotor discomfort* (O), *Disorientation* (O), and *Nausea* (N) (see Table 1). A formula provided by Kennedy et al. [29] gives a score for each subscale and a *Total Score* (TS).

Stanney et al. [53] suggests that the severity of a simulator inducing sickness can be rated as following based on the SSQ-TS: *negligible* (< 5), *minimal* (5–10), *significant* (10–15), *concerning* (15–20), and *bad simulator* (21 or higher). However, Bimberg et al. [3] argues that 20 is too low to describe a 'bad simulator' since military personnel, who may be more resilient to sickness effects, were used for Stanney's et al. [53] benchmarks. Likewise, a review of often-reported SSQ-TSs [8] argues that a SSQ-TS of at least 40 should describe a 'bad simulator'.

The fact that the SSQ was initially developed for military flight simulation research and validated on military personnel has also been used to question its validity in commercial domains and on other populations [27, 41].

There are many alternatives to the SSQ, such as the often-mentioned virtual reality sickness questionnaire (VRSQ) [33]. It has been suggested that the VRSQ may be more appropriate for measuring sickness in XR Head-Mounted Display (HMD) [41]. However, although alternatives could be more appropriate, they are also argued to be less validated than the SSQ [5, 27].

Table 1: Computation of Simulator Sickness Questionnaire (SSQ) scores. Adapted from Table 4.2 in [27].

	Weight 0-3		
SSQ Symptom	**Nausea (N)**	**Oculomotor (O)**	**Disorientation (D)**
General discomfort	+	+	
Fatigue		+	
Headache		+	
Eyestrain		+	
Difficulty focusing		+	+
Increased salivation	+		
Sweating	+		
Nausea	+		+
Difficulty concentrating	+	+	
Fullness of head			+
Blurred vision		+	+
Dizzy (eyes open)			+
Dizzy (eyes closed)			+
Vertigo			+
Stomach awareness	+		
Burping	+		
Total subscale score[a]	[N] × 9.54	[O] × 7.58	[D] × 13.92
Subscale score max	200.34	159.18	292.32
Total score (TS) = ([N] + [O] + [D]) × 3.74			
TS max = 235.62			

[a] [N], [O], [D] = the sum obtained by adding the symptoms weights as rated by respondent.

3.4.2 Fast motion sickness scale and misery scale (FMS & MISC). A single-answer self-report offers a quick way of measuring Cybersickness (CS), making it possible to administer during an experiment and get a sense of the progression of CS. Keshavarz and Hecht [30] developed and validated what they called the Fast Motion Sickness scale (FMS). The tool asks the subject to verbally rate their sickness, in a single answer, from 0 (no sickness) to 20 (frank sickness). The tool was validated in two experiments on 126 subjects by comparing it to simultaneous ratings of an

SSQ. However, a big limitation of the FMS is that it only measures sickness in one dimension (i.e., overall sickness) while CS consists of multiple symptoms.

A tool offering measurement of multiple dimensions in a single answer is the MIsery SCale (MISC) developed by Bos et al. [7]. Its validity was also checked against the SSQ. The MISC has a rating of 0 to 10, with each point corresponding to a progression of symptoms (see Table 2). It is said to have been applied successfully to many studies using visual stimuli [5]. However, the MISC does not measure the symptom category of eye strain in CS. Furthermore, since the scale is not as straight-forward as the FMS, it requires subjects to learn the rating scale in advance, to get quick responses during exposure.

Table 2: MIsery SCale (MISC) rating. Adapted from Table 4.3 in [23].

Symptom		Score
No problems		0
Uneasiness (no typical symptoms)		1
Dizziness, warmth, headache, stomach awareness, sweating, ...	Vague	2
	Slight	3
	Fair	4
	Severe	5
Nausea	Slight	6
	Fair	7
	Severe	8
	(near) retching	9
Vomiting		10

3.4.3 Physiological measurements. Psychophysiology is a research area concerned with measuring biosignals in response to psychological states. E.g., feelings of stress can induce changes in the heartbeat or skin conductance (due to sweating) that can be measured. Such measurements could offer non-intrusive and objective ways of predicting and determining a person's state of Cybersickness (CS). However, reviewed literature showed that no reliable methods have been established yet.

A literature review from 2020 by Chang et al. [10] reviewed 77 experimental studies and found that 42 applied a variety of objective measurements. The two most common were postural sway and electrophysiological changes. Chang et al. concluded that questionnaires were still the most used measurement and believed that more evidence would be needed before physiological measurements could reliably determine CS. Another literature review from 2021 [8] reviewed six papers and postulated that the best biosignals to measure CS seemed to be skin conductance and heart rate/variability. They suggested heart rate alterations would be best used to verify CS detection made by skin conductance. However, how these biosignal changes were (cor)related to CS varied in the reviewed literature.

Bos and Lawson [5] published a meta-analysis in 2021 on literature reporting on objective measures. Bos and Lawson argued that objective measures are not inherently superior to subjective measures. Some of the many limitations they pointed out with physiological measures were that: (i) there are inconsistencies in findings of their correlation to sickness; (ii) there is much variability due to confounding variables; (iii) they vary greatly between individuals and tests; (iv) collected data still has to be subjectively interpreted; (v) they do not provide a rich understanding of the symptoms. Therefore, Bos and Lawson were skeptical to objective measurements but concluded that the best way would be to include measurements of self-reports, physiological, and behavioral/performance together for more confident findings.

Initially, our study intended to incorporate physiological measurements. However, given the above findings, which indicate that these measurements are inadequately developed and challenging to analyze, their inclusion is reconsidered, primarily due to time constraints.

3.4.4 Motion sickness susceptibility questionnaire (MSSQ). A well-known observation in CS research is that there are large variabilities in sickness severity between individuals, given exposure to the same stimulus. Some individuals get easily sick when immersed in a virtual environment, while some rarely get sick [51]. Probing an individual's historical susceptibility to certain stimuli can predict their future susceptibility [19]. Measuring the susceptibility can be important to understand variances in measured CS or to screen subjects for a study.

An often-used measurement of this susceptibility is the Motion Sickness Susceptibility Questionnaire (MSSQ) by Golding [19], comprised of 54 items, adapted from a questionnaire by Reason and Brand [47]. The MSSQ probes a subject's earlier occurrences of MS with different exposures. Golding later made a shorter version called MSSQ-short [20], comprised of 18 items. In the MSSQ-short, the occurrences are rated on a four-point scale (0 = "never", 1 = "seldom", 2 = "sometimes", 3 = "often") in nine different kinds of motion exposures in the past 12 years, and in the first 12 years of one's life. A score is calculated, ranging from 0 (not susceptible at all) to 54 (extremely susceptible). Golding [20] reported on mean (12.9 ± 9.9) and median (11.3) values for a population of British university students (n = 257), useful as a benchmark.

A limitation with both these is the fact that it focuses on previous Motion Sickness experience, perhaps questioning its validity for Cybersickness research. Even though the MSSQ has been widely used in CS research, some studies have reported not finding a statistical relationship between MSSQ scores and sickness severity in virtual environments [54]. Alternatives to the MSSQ include the cybersickness susceptibility questionnaire (CSSQ) [18] and the visually induced motion sickness questionnaire (VIMSSQ) [31, 32]. However, these are not as commonly used, as the MSSQ or MSSQ-short, in the reviewed literature. Thus, being harder to make cross-study comparisons.

4 RESEARCH METHODOLOGY

4.1 Research Strategy

The aim of the study was to determine differences in Cybersickness (CS) between two different levels of virtuality in a flight simulator. The overall strategy for the study was decided to be that of experiment, an integral way of obtaining knowledge following an empiricist epistemology. An experimental design allowed for directly comparing CS between two types of simulators, and control/measure for potential confounding variables. This approach minimized biases and increased reliability by subjecting each subject with the same stimuli. Administering scientifically established measurements also made the study more replicable for other researchers. However, the disadvantages of an experimental approach can be that the data might not reflect real-world conditions, and that the subjects might behave differently than they would in a natural setting.

A case study could have been an alternative approach, allowing for a more natural setting by investigating the CS of subjects' experiences using two different types of existing simulators and collecting both qualitative and quantitative data on CS. This approach could be more in-depth, focusing on a smaller sample to provide richer and detailed data on how individuals experience cybersickness in the different simulators, but would make it less generalizable to a larger population.

Lawson and Stanney [38] state that answering questions on CS requires controlled and labor-intensive research, pointing out five recommendations: (i) assess relevant stimulus experience and past susceptibility; (ii) use large samples; (iii) use stimuli that elicit functionally relevant CS; (iv) limit the number of sessions to three and allow one week of recovery between sessions; and (v) careful establishment of measures. Following Lawson's and Stanney's recommendations, an experimental approach is argued to be more appropriate.

4.2 Data Collection

The current study decided to collect data on the dependent variable with the Simulator Sickness Questionnaire (SSQ) instrument (described in Section 3.4.1) which is well-established and used in many studies on CS. Alternatives to the SSQ could be more relevant to XR studies but were rejected for decreasing cross-study comparisons. The Fast Motion Sickness scale (FMS) was chosen over the MIsery SCale (MISC) (described in Section 3.4.2), to measure CS during exposure, for its ease of use. The chosen instruments were also recommended by Merchant and Kirollos [41] for research on CS.

The aim of measuring physiological data was reconsidered and chosen to not be pursued as the pre-study revealed that there is no established method of measuring and analyzing the data reliably. Thus, the time needed to spend on researching, learning, and obtaining equipment would not be justified compared to the unknown value it may add to the study.

4.3 Ethical Considerations

A key principle of research ethics is to not do harm. Ethical questions arise about exposing subjects to the risk of getting CS. However, the project was not designed to inflict CS on purpose. Furthermore, subjects were made aware of there being a risk of getting CS, before partaking in the experiment, and informed that they can stop the experiment at any time.

Additionally, one could question the ethics of researching for military purposes with the obvious reason that the results can lead to more people killed or environmental destruction. Hersh [21] points out the difficulty of objectively defining whether military research is ethical or not and that it is up to the individual researcher to self-evaluate the ethical consequences of their work and their own ethical standpoints. A direct consequence of our study could be less sickening XR applications that improve the training of fighter pilots and make them more efficient in killing. However, the results will be publicly available and may inform anyone and help reduce CS for everyone in any industry, such as in medical applications, making the study worth conducting.

5 DESIGN CONSIDERATIONS

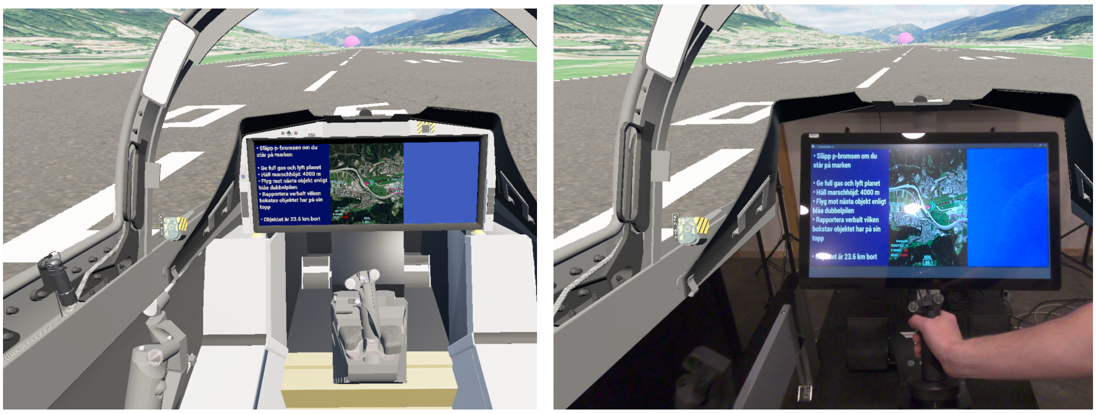
This section informs the design of the flight simulator and experiment.

5.1 Factors to Consider

There are many factors influencing CS to consider. In an experiment, one wants to be sure that the change of the independent variable is what is affecting the dependent variable. Meaning our study wants to be certain that the VR and MR flight simulator will be the main factor influencing CS. Therefore, to get reliable and valid results in the experiment it is important that both exposures are as equal as possible with only VR and MR being changed and that any other confounding variables are known. The rest of this section will detail which confounding variables are known.

The main difference between the VR and MR flight simulator would be the presentation of the cockpit and the user's body, exemplified in Figure 7. An example of various levels of virtuality in MR is given in Figure 8. The chosen virtuality level for our study is option (C), around 50% virtual, as this was considered a likely level to be implemented at FLSC, where buttons and interactions in the cockpit would be real and the terrain out the window would be virtual. In the MR version the user can see their own body interact with controls while in VR there would be no body representation. Based on this, what factors found in Section 2.3 can be expected to influence CS between

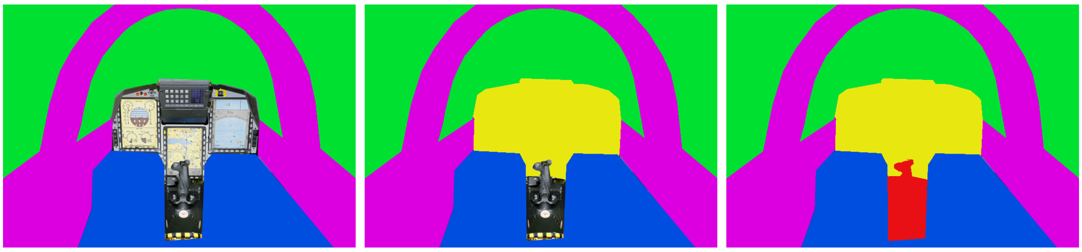
VR and MR? Following is a brief analysis of which factors may be changing and how they will be controlled in the experiment, i.e., measured or made sure to not affect the dependent variable, with Table 3 giving an overview.



(a) Virtual Reality **(b) Mixed Reality**

Figure 7: Comparison of the two virtuality levels in the developed flight simulators.

(a) Real reality (0% virtual) **(b) Mixed reality (30% virtual)** **(c) Mixed reality (50% virtual)**



(d) Mixed reality (70% virtual) **(e) Mixed reality (90% virtual)** **(f) Virtual reality (100% virtual)**

Figure 8: Examples of different levels of virtuality, ranging from 0% to 100% (approximate) virtual environment of the field of view. The current study employs option (c). From [13] with permission to use.

5.1.1 Individual considerations. The individual factors are extensive but, since the same individuals will be exerted to both exposures, CS is not expected to be affected by individual factors between the exposures, apart from: the *level of experience*. That is, habituation/adaption to stimuli (e.g., sensory organ adaptation, learning etc.) from the first session may carry over to the next session. To control this, Lawson and Stanney [38] recommends a limit of three sessions and to allow one week of recovery between sessions for VR studies. However, due to time constraints and the

Table 3: Anticipated changes of factors, influencing cybersickness, between Virtual Reality and Mixed Reality.

Factor	May differ between exposures?	Will be controlled?
	Individual Factors	
Past response to exposure	No	Yes – measured with MSSQ-short
Level of experience / adaptation to stimuli	Partly – possible cross-over session experience	Yes – measurements to be assessed afterwards
Any other individual factor	No	Yes – same individuals
	Technological Factors	
Display		
Time lag / Latency	Maybe – Hard to estimate	No
Screen flicker	Maybe – Hard to estimate	No
Frame rate	Maybe – Hard to estimate	Yes – will be measured
Any other display factor	No	Yes – same equipment
Optical		
Focal distance & image plane	Partly – VST area in the MR will have a focus decided by the camera	No
Any other optical factor	No	Yes – same equipment
Spatial tracking		
Any spatial tracking factor	No	Yes – same equipment
Audio		
Block out external noise	No	Yes – same equipment
	Operational Factors	
Head movement	Yes	No
Rate of linear & rotational acceleration	Yes	No
Luminance	Yes	No
Vection	Yes	No
Avatar / Body	Yes	No
Duration since last exposure	Yes	No
Visual scene density	Yes	Somewhat – same flight path
Global visual flow	Yes	Somewhat – same flight path
Mental distraction	Maybe – unknown if changed	Somewhat – same set of tasks
Graphic realism	Maybe – unknown if changed	No
Rest frame	Maybe – unknown if changed	No
Any other operational factor	No	Yes – same equipment/operation

availability of subjects, only a one-day recovery minimum will be applied. Post experiment, the CS measurements can also be statistically assessed for significant differences between sessions. If the CS has changed from the first to second session for the whole sample, it may show that adaptation has occurred.

5.1.2 Technological considerations. The main difference between the two versions in this category is related to the VST technology displaying the real environment in the MR version, which is affected by the cameras and the MR merging performance of the software. The related factors are: *latency*, *frame rate*, *screen flicker*, and *focal distance & image plane*. The former three can clearly differ depending on the software and hardware but it is hard to estimate how. The last factor pertains to the fact that poor focus simulation and depth information can influence CS (as touched upon in Section 3.2.3) and in MR the focus of the real environment is relied on cameras with technology such as auto-focus. Controlling all these factors would be hard and time consuming, apart from frame rate which can easily be measured to later evaluate if differences occurred.

5.1.3 Operational considerations. The main operational differences will be the look of the cockpit, the user's body, and what the user is doing inside the simulator. These include *head movements*, *rate of linear & rotational acceleration*, *luminance*, *vection*, *avatar/body*, *duration since last exposure*, *visual scene density*, and *global visual flow*. These may differ between the exposures depending on how the user is flying, where they are looking, how they experience vection etc. Many of these factors will not be controlled to limit the scope of the study. Furthermore, the study wants to let the users fly as they feel they need to, as in a real context, and not limit their freedom of control. Which would make it a roller coaster simulator instead. However, to have some form of structure, a set of tasks will be designed that will be equal between the two exposures, which all subjects will have to follow. The task design is described in Section 5.3.

Furthermore, avatar/body (i.e., sense of embodiment) will be different as the user's body will be visible in MR but not represented in VR, which can influence the CS. Implementing a full-body virtual avatar is possible but not in the scope of our study. Regarding duration of exposure, the recommendation to have an exposure time of at least 20 minutes [8, 34] should be followed. Lastly, the mental distraction, graphic realism, and rest frame, may differ depending on how the user will perceive these things between VR and MR. These could be measured in some ways but will not be investigated, to limit the scope of the study.

5.2 Design Requirements

To make the flight simulator (i.e., exposure) closer to a real-world context and more relevant to the operations at FLSC, the flight simulator and tasks should resemble how pilots at FLSC normally would interact with a flight simulator. The technical manager at FLSC held a brief introduction to how pilots train at the facility and the following insights were gathered. Firstly, pilots mostly look at the Head-Down Display (HDD), second most at the head up display (HUD), and the least outside on the environment. HDD is essentially instruments inside the cockpit and HUD is information displayed on a piece of glass, overlayed when looking out the canopy. Secondly, the cognitive load varies, but are usually high with the pilot having to interact a lot with the HDD. Thirdly, during an air combat duel situation, most of the interactions can be done via the hands on throttle and stick (HOTAS).

Furthermore, as mentioned in Section 4.1, Lawson and Stanney [38] pointed out that one should use stimuli that elicit functionally relevant CS. Meaning, the exposure should be provocative enough that CS is elicited, or nothing can be measured. Likewise, the other way around, if the exposure is too provocative the participants may not be able to complete the full duration of the test.

5.3 Designing the Simulator and Tasks

With the above sections in mind, the simulator and tasks were created as following. The participant takes off on a runway in Innsbruk, Austria and flies in a large figure eight around western Austria for 30 minutes. The location was chosen for its varying terrain height. The participant has to manually keep an altitude of 4000 meter above sea level. The current altitude is displayed on the HDD. The flight task is to fly towards a large pink ball (ø = 500 m) in the terrain, which often can not be directly seen visually and, thus, one need to fly by looking at the map in the HDD. The pink ball acts as a checkpoint and the participant has to observe an alphabetic letter on top of it, and speak it out loud to get a new checkpoint. Once every minute, an FMS rating pops up on the HDD which the pilot has to interact with using the HOTAS. Lastly, throughout the session one has to interact with a space-shooter-like game element in the HDD, collecting points.

These tasks of keeping the correct altitude, flying towards a checkpoint, observing the letters on the checkpoints, and attending the FMS rating and space-shooter game, will hopefully ensure that the gaze will alternate between the HDD and terrain, keep the pilot cognitively busy, and lead to a functionally relevant CS.

6 METHOD

6.1 Subjects

Participants (n = 29) were subjects aged 23-62 (M = 40, SD = 12) of which one was female. The chief sampling techniques were convenience and snowball sampling – recruited via internal announcements and spread of word, asking for volunteers to sign up. No one had issues with their vestibular sensory system, when asked. They could wear their glasses while wearing the Head-Mounted Display (HMD), although five subjects had varying minor issues with their vision that was not corrected. No one terminated their session due to discomfort, whether from Cybersickness (CS) or any other cause.

On a scale of no experience (0) to a lot of experience (3), the sample had moderate experience in using flight simulators (M ± SD = 1.8 ± 0.9), close to no experience in flying real aircrafts (0.4 ± 0.8), and moderate experience in playing video games (2.2 ± 0.8). Furthermore, the sample could be seen as less susceptible to CS, with a lower MSSQ-short score (11.1 ± 8.1) compared to the benchmark (12.9 ± 9.9) of Golding [20].

6.2 Materials

A flight simulator was developed in Unreal Engine 5.1 [16] using the deferred rendering pipeline, JSBSim 1.1.13 [25] for simulating realistic flight dynamics, Cesium [9] plugin for terrain generation, and a modified 3D model of a JAS 39 Gripen fighter jet. The aircraft was given the flight dynamics of an F16/A, included with the JSBSim. In VR all the instruments and buttons in the cockpit were removed, except for a virtual display in front of the subject with flight data and flight instructions. In MR the cockpit was replaced by the Video See-Through camera, with Varjo's stencil masking technique, showing a real-world digital display and the real-world surrounding area (see Figure 7). More on the simulator design is in Section 5.3 (the only deviation is that the space-shooter game was removed, the final look is seen in A.2).

A Windows 10 computer with, Nvidia GTX 3080, and 10th generation Intel i7 powered the XR HMD Varjo XR-3 (see Appendix A.3 for specifications) with Varjo Base 3.10 software. Four Steam VR base stations [22] were used to track the HMD. The flight simulator was too performance heavy to be running at maximum resolution. Therefore, the focal displays were turned off and resolution lowered to medium inside Varjo Base, changing the final resolution to 1444 x 1236 with 33 Pixels Per Degree (PPD) according to Varjo Base.

6.3 Experiment Design

The main objective of this study was to determine differences in elicited CS between a MR and VR flight simulator. The experiment design used was exposure differences through within-subjects testing of the two virtuality exposures. The independent variable was the VR and MR cockpit environment. The dependent variable was CS, indexed with Simulator Sickness Questionnaire (SSQ) and Fast Motion Sickness scale (FMS).

6.4 Pilot Study

To evaluate the prototype and experimental procedure, a pilot study was conducted on two senior researchers, one being a naïve subject and one who had tried an earlier version. The pilot study mainly revealed that the task of attending the space-shooter game was too cognitively overwhelming and was thus removed before the main study.

6.5 Main Study Procedure

The main study was conducted over a period of four weeks in a quiet room at FOI, in Stockholm, during May-June, 2023. Subjects partook individually in two sessions – one MR and one VR – with at least one day of recovery between the sessions. The sessions were counterbalanced so that half of the subjects began with MR and the other half with VR, with the first subject being randomly assigned. Overview of the procedure is shown in Figure 9.

The subjects were briefly introduced to the study, being told that the interest of the study is peoples experience and well-being in two different simulators and that they are free to end their participation anytime. After signing a consent form, they filled out a demography questionnaire, Motion Sickness Susceptibility Questionnaire (MSSQ)-short and pre-exposure SSQ. Thereafter, the subjects were given instructions and demonstrations on what their tasks during the flight were and how to fly in the simulator. They were then helped to put on the HMD correctly and asked to fly a short practice flight to demonstrate that they had understood the tasks and procedure.

Thereafter, the simulator was rebooted and participants were instructed to don headphones playing dynamic jet engine sounds and wind noise. This marked the commencement of the approximately 30-minute flight exposure. The experimenter sat beside, observed what happened in the simulator on a display, and took notes. If the subject asked something during flight they were answered, otherwise there was no communication directed towards the subjects. The subjects followed the flight task of checkpoints as described in Section 5.3, verbally stating what letter they saw at every checkpoint. Stating the correct or incorrect letter was noted manually by the experimenter. The FMS was automatically administered every minute in the simulator.

Directly afterwards, the post-exposure SSQ was administered and an open discussion was held where the subject was free to talk about their experiences if they wished. The HMD lenses and padding were cleaned after every session.

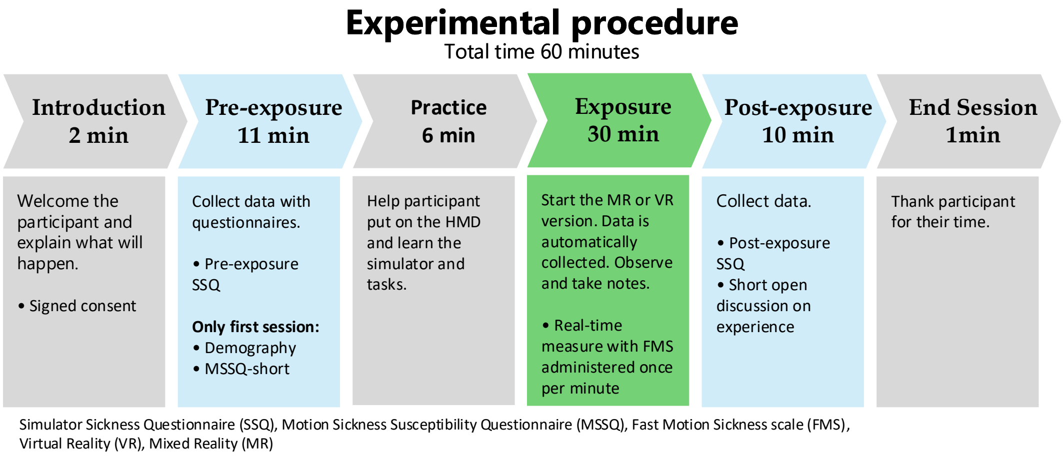


Figure 9: Overview of the main study procedure. Performed twice by each subject, once with Virtual Reality exposure and once with Mixed Reality.

6.6 Data Collection

Demography questionnaire and MSSQ-short were collected only in the first session. Pre- and post-exposure SSQ were administered in both sessions. A few custom experience questions were also included in the post-exposure SSQ. During exposure, FMS was administered every minute. Notes on observations and subjects' comments were taken throughout the sessions by the experimenter. The simulator automatically saved several data parameters in a CSV-file every 0.1 second: timestamp, the average frame rate, altitude, speed, location & rotation, and the momentaneous rotation rate.

The FMS and passed/failed checkpoint were saved in the same file with timestamps. All data was separable by subject, exposure version, and session number.

6.7 Data Processing

Each subject was anonymized with a unique ID number in all the data. All questionnaire data were imported into Windows Excel, in which SSQ and MSSQ-short scoring were computed following [3] and [20] respectively. The post-exposure SSQ scores were subtracted with their respective pre-exposure baseline scores. This resulted in a few negative values which could be interpreted as the exposure having a positive effect on the subjects. However, following the reasoning in [3], negative scores were turned into zeroes, meaning the exposure is seen as having a no negative instead of a positive effect on the subjects. Everything was then summarized into one sheet which was imported into SPSS 28.0 for statistical analyses.

All the CSV files were imported into a single Excel sheet, known missing values were added, double-checked for unknown missing values, and then imported into SPSS for statistical analyses. The handwritten notes were written into digital format.

7 RESULTS & ANALYSIS

Results are presented in this section and analyzed with statistical methods. For testing differences of means, Wilcoxon Signed Rank Test (WSRT) was used because this is a non-parametric statistical test that can be used for within-subjects (i.e., paired samples / repeated measure) data that is not uniformly distributed [41]. Effect sizes for significant results with WSRT were calculated with the formula $r = z/\sqrt{2n}$, and interpreted following Cohen's criteria [11]. The Shapiro-Wilk test was used to confirm the non-uniform distribution of variables. Significance level was set to $p < .05$ for all tests, following general research recommendations. The data compared with WSRT was Simulator Sickness Questionnaire (SSQ) scores between Virtual Reality (VR) and Mixed Reality (MR), SSQ subscale ordering in VR and MR, SSQ subscale scores between VR and MR, Fast Motion Sickness scale (FMS) between VR and MR, SSQ and FMS between first and second session. A Spearman correlation test comparing SSQ Total Score to MSSQ-short scores was performed to determine the relationship between history of sickness and Cybersickness. These statistical analyses, descriptive statistics and analysis of qualitative data are described below.

7.1 Simulator Sickness Questionnaire

Results and analyses in this section address all three hypotheses of the study. Means of every SSQ score for the whole sample was computed and the pre-exposure was subtracted from the post-exposure SSQ of the 29 subjects (negatives being zeroed as described in Section 6.7). The results were divided by VR vs. MR, as seen in Table 4 and visualized in Figure 10.

Table 4: Descriptive statistics of all Simulator Sickness Questionnaire scores.

	Virtual Reality				Mixed Reality			
	TS	**N**	**O**	**D**	**TS**	**N**	**O**	**D**
	Pre-exposure SSQ scores							
Mean	10.8	6.6	11.0	10.6	8.6	5.6	10.0	5.8
Median	3.7	0.0	0.0	0.0	3.7	0.0	7.6	0.0
SD	13.5	19.7	19.7	23.7	11.6	13.1	14.8	18.8
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	44.9	66.8	91.0	97.4	52.4	66.8	60.6	97.4
	Post-exposure SSQ scores							
Mean	25.0	18.1	20.9	28.3	20.2	11.2	19.3	23.5
Median	18.7	9.5	15.2	13.9	18.7	0.0	15.2	13.9
SD	21.5	20.5	24.6	35.8	15.6	17.5	21.6	27.6
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	74.8	66.8	83.4	125.3	52.4	76.3	75.8	111.4
	Final SSQ scores							
Mean	15.6	12.5	12.3	20.2	12.6	8.2	10.7	19.7
Median	11.2	9.5	0.0	13.9	11.2	0.0	0.0	13.9
SD	18.5	16.7	20.1	33.4	13.8	16.5	18.6	27.2
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	71.1	57.2	75.8	125.3	44.9	76.3	75.8	111.4

Simulator Sickness Questionnaire (SSQ), Standard Deviation (SD), Total Score (TS), Nausea (N), Oculomotor discomfort (O), Disorientation (D)

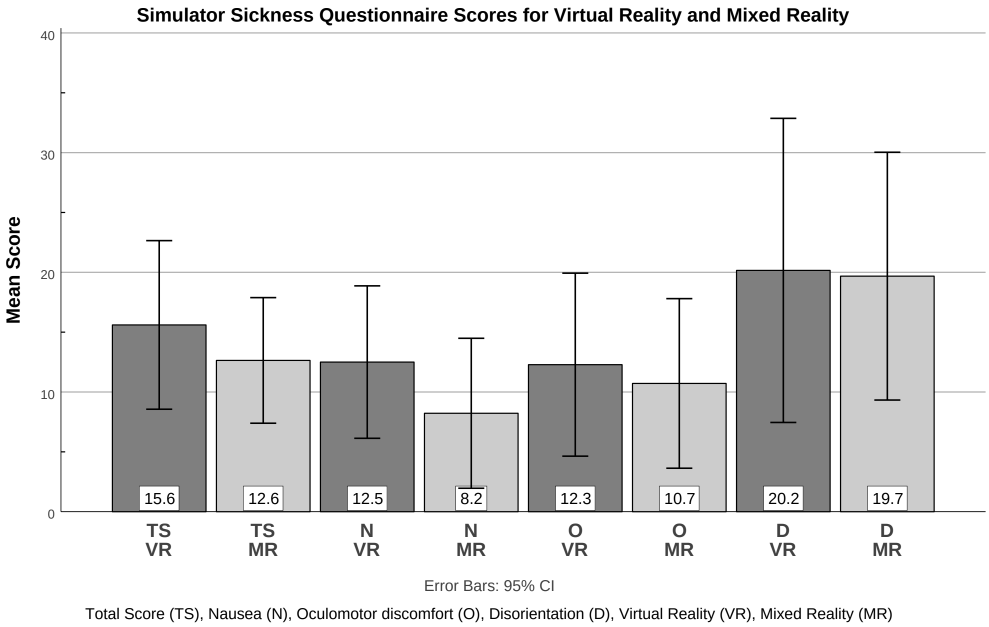


Figure 10: All (final) scores of the Simulator Sickness Questionnaire in Virtual Reality (dark gray) and Mixed Reality (light gray).

Table 5: Results of Shapiro-Wilk's test (W) of normality (p < .05 indicates non-uniform distribution)

	Virtual Reality SSQ				Mixed Reality SSQ			
	TS	**N**	**O**	**D**	**TS**	**N**	**O**	**D**
W(29)	.891	.765	.631	.648	.914	.573	.671	.756
p	.006	<.001	<.001	<.001	.022	<.001	<.001	<.001

Simulator Sickness Questionnaire (SSQ), Total Score (TS)

Nausea (N), Oculomotor discomfort (O), Disorientation (D), Statistical significance (p)

7.1.1 SSQ total score VR vs. MR. In Figure 11 it can be seen that many subjects had a smaller SSQ Total Score (TS) in MR and for the whole sample, the VR exposure had a higher mean SSQ-TS (M = 15.6, SD = 18.5) compared to the MR (M = 12.6, SD = 13.8). This indicates that CS was slightly more severe in VR than MR, supporting H1. Visual inspection of their histograms and Shapiro-Wilk's tests (p < .05) showed that none of the variables were normally distributed (see results in Table 5). Therefore, WSRT was performed revealing that the difference in TS between VR vs. MR was not statistically significant, z(29) = -.78, p = .44. Meaning that the difference could be a result of randomness.

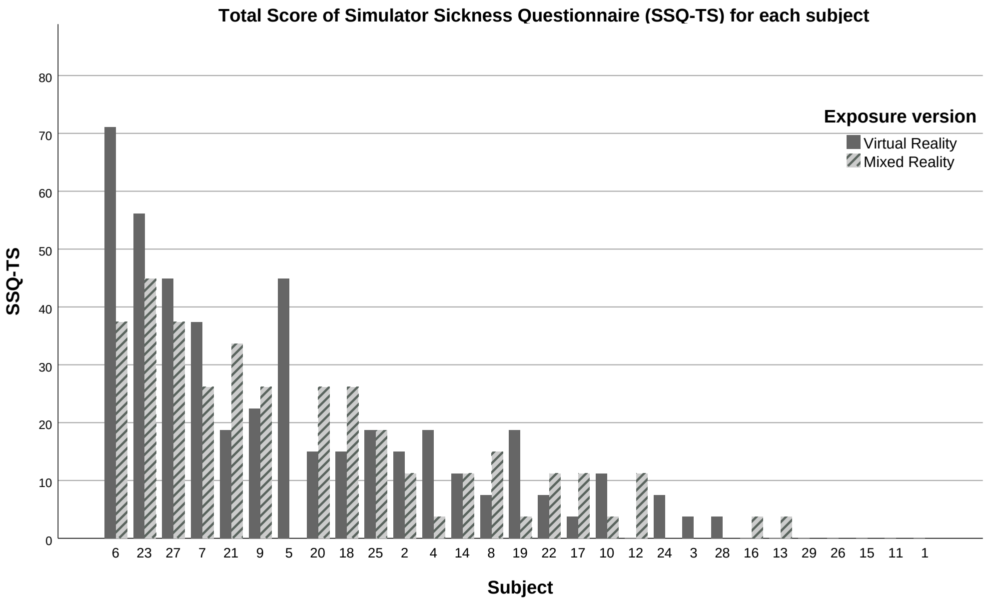


Figure 11: Total Score of the Simulator Sickness Questionnaire (SSQ-TS) for each subject in Virtual Reality and Mixed Reality. An absent bar signifies a score of zero.

7.1.2 SSQ subscale scores. The SSQ subscales are Nausea (N), Oculomotor discomfort (O), and Disorientation (D). The subscale ordering for VR was D>N>O (20.2 > 12.5 > 12.3) and for MR it was D>O>N (19.7 > 10.7 > 8.2) (see Table 4). The VR exposure shows a slightly higher scoring across every subscale. The subscale D seem to have a clear gap from the other subscales, in both VR and MR. Indicating that disorientation symptoms was predominant in VR, supporting *H3*, and in MR, refuting *H2*.

Since the second and third highest subscales are so small in difference their ordering may just be random. However, significance between the highest and other subscales were tested, in both exposures. Visual inspection of their histograms and Shapiro-Wilk's tests ($p < .05$) showed that none of the variables were normally distributed (see results in Table 5). Therefore, WSRTs were performed (see results in Table 6), revealing that only for MR D vs. N was there a statistically significant difference, z(29) = -2.54, p = .011, with a moderate effect size (r = .33). Indicating that disorientation was more prominent than, at least, nausea in MR. Although VR D vs. O was close to significance also (p = .086), suggesting disorientation could be more prominent than oculomotor discomfort in VR.

Table 6: Wilcoxon Signed Rank Tests (z) on the prominence of disorientation.

	Virtual Reality		Mixed Reality	
	z(29)	***p***	**z(29)**	***p***
D vs. N	-1.16	0.245	-2.54	0.011[a]
D vs. O	-0.92	0.356	-1.72	0.086

Nausea (N), Oculomotor discomfort (O),
Disorientation (D), Statistical significance (p)

[a]Effect size r = 0.334

Lastly, the differences in SSQ subscale scores between VR vs. MR were statistically tested. WSRT was performed to compare the SSQ scores between VR and MR and determine if there was any statistically significant difference. The outputs revealed that any differences were not significant ($p > .05$), as seen in Table 7. This indicates that no category of symptoms were more prominent comparing between the exposures.

Table 7: Wilcoxon Signed Rank Tests (z(29)) on differences between Virtual Reality and Mixed Reality for all Simulator Sickness Questionnaire scores.

Score of comparison	M ± SD VR	M ± SD MR	Output	Decision	Related study hypothesis
SSQ TS	15.6 ± 18.5	12.6 ± 13.8	z = -.78, p = .44	Retain null hypothesis, difference equals 0	H1
SSQ N	12.5 ± 16.7	8.2 ± 16.5	z = -1.50, p = .13	Retain null hypothesis, difference equals 0	
SSQ O	12.3 ± 20.1	10.7 ± 18.7	z = -.67, p = .51	Retain null hypothesis, difference equals 0	
SSQ D	20.2 ± 33.4	19.7 ± 27.2	z = -.36, p = .72	Retain null hypothesis, difference equals 0	

Simulator Sickness Questionnaire (SSQ), Nausea (N), Oculomotor discomfort (O), Disorientation (D),
Mean (M), Standard Deviation (SD), Statistical significance (p), Virtual Reality (VR), Mixed Reality(MR)

7.2 Fast Motion Sickness Scale VR vs. MR

Results and analyses in this section only address the first hypothesis of the study. Each subject's Fast Motion Sickness scale (FMS) ratings (n = 872 in VR and n = 867 in MR) were computed into a mean value representing their rating for the whole session and grouped by exposure version, as illustrated in Figure 12. Inspecting their histograms and performing a Shapiro-Wilk's test showed that the data were not normally distributed in neither VR (W = 0.71, n= 29, p < .001) or MR (W = 0.68, n = 29, p < .001). A Wilcoxon Signed Rank Test showed that the mean FMS in VR (M ± SD

= 1.34 ± 2.04) was significantly higher than in MR (0.83 ± 1.35), z(29) = -2.11, p = .035, with a small effect size (r = .28). Indicating that CS was more severe in VR.

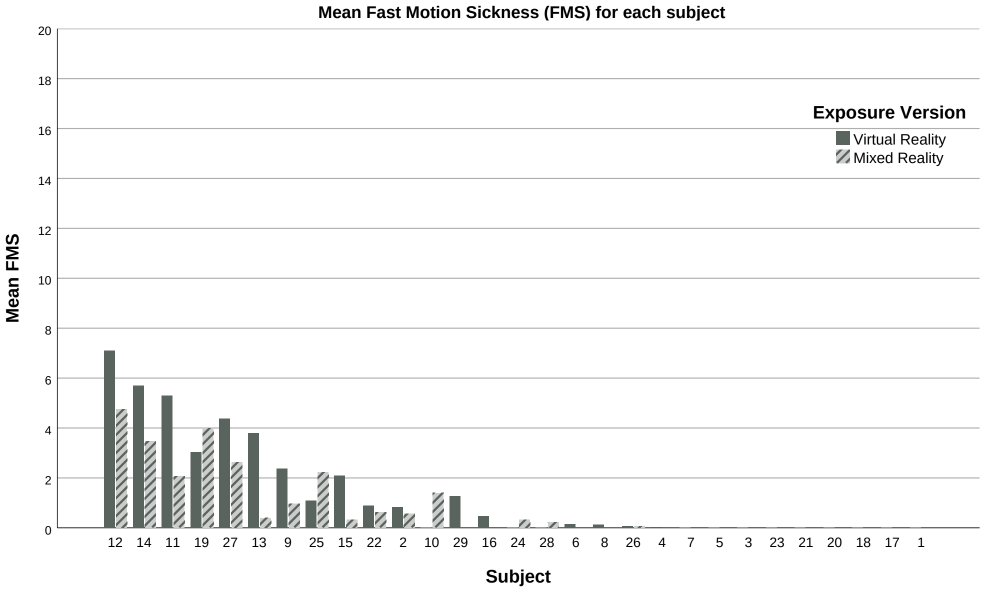


Figure 12: Mean Fast Motion Sickness scale (FMS) rating for each subject in Virtual Reality and Mixed Reality. An absent bar signifies a score of zero.

7.3 Correlation Analysis Between MSSQ-short and SSQ

To confirm that the MSSQ-short has a predictive power on CS susceptibility correlation analysis was conducted. Visual inspection of the histogram of MSSQ did not show a definitive normal distribution. A Shapiro-Wilk's test (W = .93, n = 29, p = .07) revealed that it was approximatively normally distributed. However, the SSQ-TS scores are not normally distributed, as seen in Table 5. Therefore, Spearman's correlation test was performed and revealed that there was a strong positive correlation between the MSSQ score and SSQ-TS score in both VR, r(29) = .59, p < .001, and MR, r(29) = .59, p < .001.

7.4 Cross Session Adaption

Analyses were conducted to compare CS between the sessions to test if the subjects may have become adapted to the exposure from the first (S1) to the second session (S2).

Grouping the mean SSQ-TS by session showed a slight increase from S1 (M ± SD = 13.3 ± 16.7) to S2 (15.0 ± 16.1). Indicating that adaption did not occur. However, the difference was tested. Inspecting their histograms and performing a Shapiro-Wilk's test showed that the data were not normally distributed in either S1 (W = .786, p < .001) or S2 (W = .850, p < .001). A WSRT revealed no significant difference in SSQ-TS means in S1 vs. S2, z(29) = -.86, p = .39).

Grouping the subjects' mean FMS rating by session showed a slight decrease from S1 (1.13 ± 1.78) to S2 (1.05 ± 1.72). Indicating that adaption may have occured. Inspecting their histograms and performing a Shapiro-Wilk's test showed that the data were not normally distributed in either S1 (W = .685, p < .001) or S2 (W = .678, p < .001). A WSRT revealed that there were no statistically significant difference in FMS means between S1 vs. S2, z(29) = -.56, p = .57. Thus, the slight difference is negligible and does not indicate adaption to the exposure.

7.5 Frame Rate VR vs. MR

The mean frames rate was negligibly higher in VR (M = 36.5, SD = 3.7, n = 527 000) than in MR (M = 35.3, SD = 3.5, n = 529 000). However, looking at Figure 13, VR has two peaks indicating a more inconsistent frame rate compared to the frame rate in MR, possibly affecting CS for the worse, by reasoning that a "jumping" frame rate may be more noticeable than a constant frame rate.

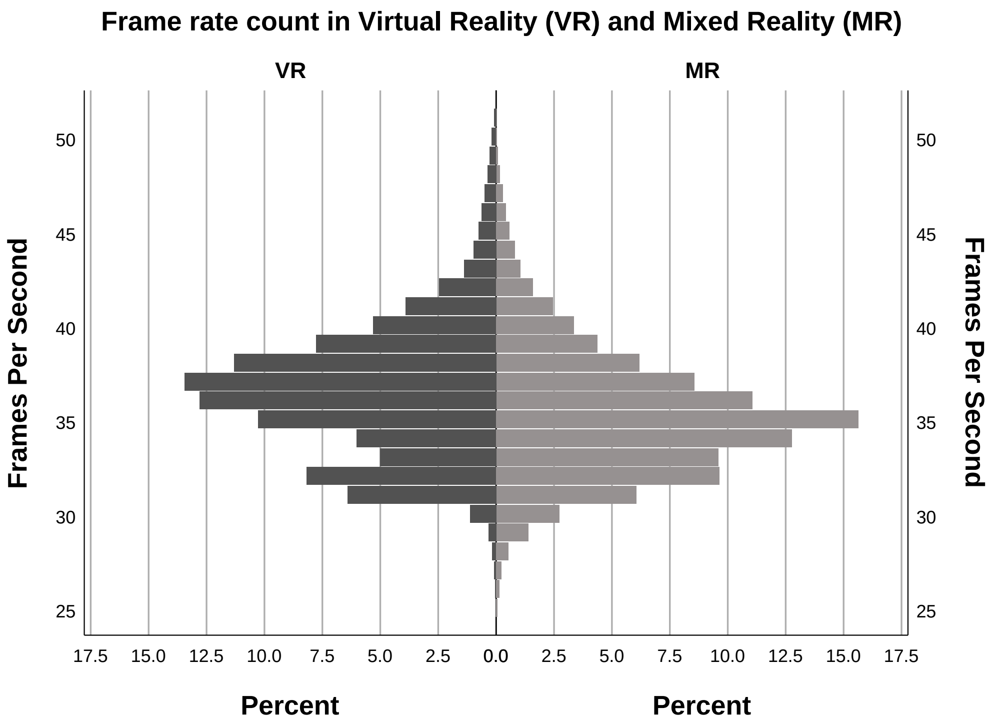


Figure 13: Frame rate count in percentage as measured in Virtual Reality (dark gray) vs. Mixed Reality (light gray).

7.6 Fast Motion Sickness Scale by Duration

All the FMS ratings were plotted against the exposure duration, as seen in Figure 14, showing that the CS increased over time, with somewhat of a peak around 20 minutes. Indicating that the 30 minute exposure was long enough to reach maximum CS, although it does not show for how many in the sample.

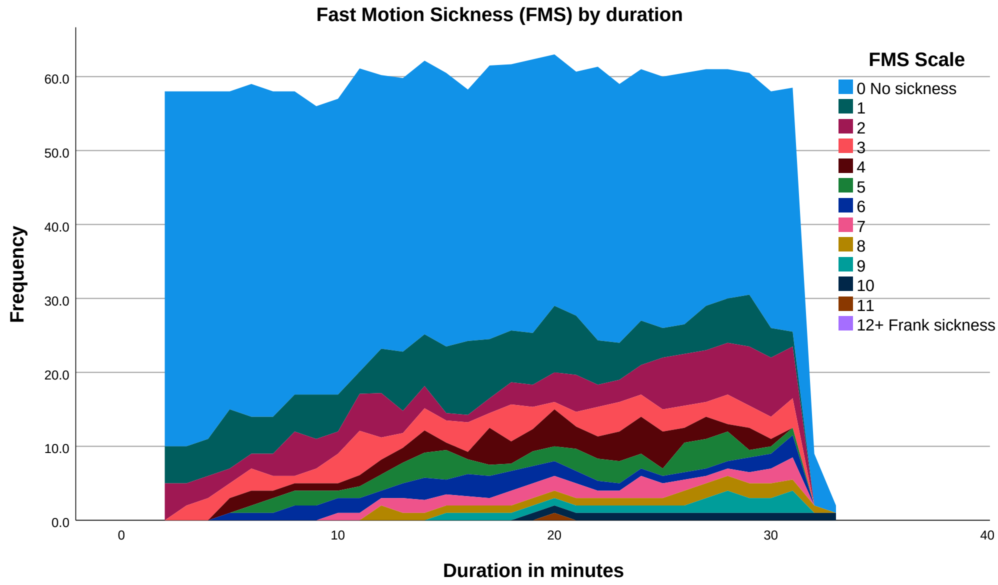


Figure 14: All Fast Motion Sickness ratings by exposure duration. The highest rating was 11 at the 20 minute mark. The drop at the end is due to the approximate cut-off time of the exposure.

7.7 Post-exposure Questions

A few post-exposure questions probed subjective experiences related to confounding factors in Section 2.3.3. Table 8 shows what factor associates with each question. The Figure 15 shows the mean rating of each question for VR and MR. The differences between VR and MR are deemed negligible and, thus, will not be analyzed further.

Table 8: Post-exposure experience questions with associated confounding factor.

Question	Factor
How well did you have the illusion of moving through space?	Vection
How realistic did the graphics feel?	Graphic realism
How well did it feel like your body was in the virtual airplane?	Sense of embodiment

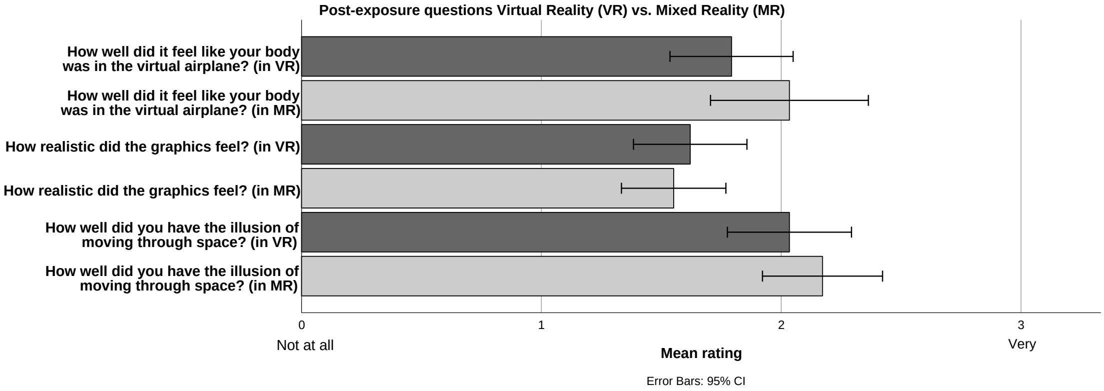


Figure 15: Mean ratings of post-exposure experience questions in Virtual Reality (dark gray) vs. Mixed Reality (light gray).

7.8 Qualitative Data

The qualitative data consisted of 60 observational notes and 171 comments. Familiarization with the data began and observations and comments that were irrelevant were deleted from the data. 17 observations and 116 comments were then coded where each observation or statement were given a code, resulting in 96 unique codes. Separating the codes into VR and MR did not reveal any major differences that can be seen as a reflection of the entire data set. However, the following results were worth noting.

Some stated that they felt completely unaffected after exposure, a few stated they felt more alert or relaxed, while many complained about HMD issues such as it being warm, heavy, and pressing hard on the head. Those who felt affected mainly complained about headache, eye strain, and/or drowsiness. The majority stated that they felt less sick than they expected to. Five subjects stated that their symptoms lingered on for quite a while continuing their workday, with one feeling drowsy the rest of the day. Sighing and yawning were commonly observed. A few mentioned they could employ techniques to feel less sick, such as: limit their maneuvering of the aircraft, fixate their gaze on a distant point, and limit their head-movement.

Many expressed being more positive to the MR version, stating that seeing their hands was good or that they felt more immersed in MR. Two stated that they felt the real world in MR gave a more stable frame of reference, and only one stated they preferred the VR version. Overall, most felt the simulator had issues with flickering, poor resolution, occasional low frame rate, and loading of terrain. Many also felt the VST had blurry image when moving their heads, that the auto-exposure was annoying, and that the auto-focus was slow.

8 DISCUSSION & CONCLUSION

The primary objective of this study was to answer the following research question: *How does cybersickness compare between a VR and MR flight simulator, using a video-see-through extended reality head-mounted display?*

Based on previous research, three hypotheses were formed to investigate the research question. A Virtual Reality (VR) and Mixed Reality (MR) flight simulator was developed and tested for exposure differences using a within-subjects experimental design. The dependent variable being Cybersickness (CS), measured with the Simulator Sickness Questionnaire (SSQ) and the Fast Motion Sickness scale (FMS). Statistical analyses were conducted to evaluate the hypotheses.

8.1 H1: The Severity of cybersickness VR vs. MR

***H1**: The severity of cybersickness will be less severe in the MR flight simulator compared to the VR flight simulator.*

In our study, the SSQ Total Score (TS) indicated less severe CS in the Mixed Reality (MR) flight simulator, although it did not achieve statistical significance. However, the mean ratings from the FMS showed a statistically lower CS within the MR scenario. Taken collectively, these outcomes lend support to our first hypothesis. Nonetheless, further investigation is necessary to extend these findings to a broader population and the broader context of MR, transcending the scope of our study. This discovery aligns with prior research [26, 27, 35], which underscored the anticipation of a less severe CS in MR scenarios utilizing Optical See-Through (OST) Augmented Reality Head-Mounted Display (HMD)s.

Our study found a mean SSQ-TS of 15.6 for VR. A literature review from 2020 [50] showed that reported SSQ-TS, for VR, ranged 14.3-35.3, across 55 studies. Which, comparatively, puts our SSQ-TS for VR in the lower range.

For MR, our study found a mean SSQ-TS of 12.6. A literature review from 2021 [56] showed that reported SSQ-TS ranged 0-20, when using OST AR HMD technology. Using the same technology, two later studies showed a mean SSQ-TS of 11.6 in a low-virtuality MR exposure and 27.0 in a high-virtuality MR exposure [35] and a mean SSQ-TS of 13-40 [26]. Comparatively, this puts our SSQ-TS of 12.6 for MR in the lower range.

Following Stanney's et al. [53] categorization of SSQ-TS (see Section 3.4.1), a SSQ-TS of 15.6 could be considered *significant* or *concerning* symptoms, while following Caserman's et al. [8] reasoning it may be rated as *minimal* symptoms. Following Bimberg's et al. [3] reasoning, 15.6 would likely also be considered less than *concerning*. We also suggest that the cut-off points proposed by Stanney et al. are too conservative and we posit that the SSQ-TS of 12.6 (MR) and 15.6 (VR), found in our study, indicates either *minimal* or *significant* symptoms elicited by our flight simulators.

8.2 H2: The predominant symptom profile in MR

***H2**: Oculomotor (eye strain) symptoms will be predominant in the MR flight simulator.*

The symptom profile for MR found in our study was D>O>N (19.7 > 10.7 > 8.2). The disorientation (D) symptoms scored higher than the other two symptom categories of oculomotor discomfort (O) and nausea (N). Although the D-score was only significantly higher than N, we argue that D was the predominant symptom profile for the MR flight simulator, refuting our second hypothesis.

The above stands in contrast to previous research mentioned in the current study, where two experiments [23, 26] reported a symptom profile of O>D>N and a literature review [56] where the authors pointed out that O is predominant in general. A reason for the differing symptom profile in our study could be that previous research is done using Optical See-Through (OST) technology, while for the current study we used Video See-Through (VST) technology. Furthermore, a symptom profile predominated by Disorientation is what previous research has reported for VR, as discussed in the next section, suggesting that MR experienced with a VST HMD elicit a similar symptom profile as in VR.

8.3 H3: The predominant symptom profile in VR

***H3**: Disorientation symptoms will be predominant in the VR flight simulator.*

The symptom profile for VR found in our study was D>N>O (20.2 > 12.5 > 12.3). Disorientation (D) scored higher than the other two symptom categories, although without statistical significance. Our third hypothesis can therefore not be supported. However, previous research has established D to be predominant in VR [50, 53]. A reason for why our study did not reach statistical significance could be that the sample was desensitized to disorientation due to the moderate experience of using flight simulators the sample had. We cannot posit that any symptom category was predominant for VR in our study, although the result seem to be in line with previous research.

8.4 What affected the outcome of severity in cybersickness?

A pre-study assessed what factors could be contributing to discrepancies in Cybersickness (CS) between the two flight simulators (see Section 5), divided into three categories: individual, technological, and operational factors. As outlined in Table 3, 15 factors were identified with potential to impact CS: level of experience, latency, screen flicker, frame rate, head movement, rate of linear & rotational acceleration, luminance, vection, avatar/body, duration since last exposure, visual scene density, global visual flow, mental distraction, graphic realism, and rest frame.

The current study can likely rule out the influence of the sole "individual" factor: *level of experience*, i.e., that the sample was adapted, or sensitized, to the CS between the first and second session. This cross session adaption was tested by comparing the SSQ-TS and FMS between VR and MR, and did not show a statistically significant difference. Perhaps due to the counterbalancing of which exposure each subject began with.

Among the technological factors, our study saw a discrepancy in the frame rate between the exposures, with VR having more inconsistency, thus, possibly eliciting more CS. If, or how, any other technological factor varied is unknown.

Lastly, among the operational factors, in the post-exposure SSQ a few extra questions tried to probe the experience of the operational factors: vection, graphic realism, and avatar/body (as sense of embodiment). Ratings of those questions were compared between VR and MR visually and did not reveal any large discrepancies. These are complex experiences and likely require more advanced measuring than a single question. Therefore, the study cannot posit how they affected the outcome of the experiment. Nonetheless, when asked to talk about their experiences, two subjects explicitly stated that the real world seen in MR gave a more stable frame of reference. This is supporting the rest frame hypothesis (described in Section 3.2.4) and is one of the operational factors (see Section 2.3.3). Hence, rest frame could be a possible factor why our study saw less severe CS in MR. If, or how, any other operational factor varied is unknown.

In summary, among the 15 possible factors that could affect the outcome of CS between VR and MR, *level of experience* can be ruled out, while *frame rate* and *rest frame* could have contributed. The role of the other 12 factors are unknown.

8.5 Additional Aims

The study had four additional aims: (i) provide an overview of Cybersickness (CS); (ii) prototype an eXtended Reality (XR) flight simulator with the Unreal Engine platform; (iii) test a method of measuring physiological data and correlate it with CS; and (iv) indicate how severe CS the simulator users at the Swedish Air Force Combat Simulation Centre (FLSC) could expect from a XR flight simulator.

Our study addresses these aims as follows: (i) a pre-study consisting of chapters 2 and 3 provides an overview of CS; (ii) informed by chapter 5, a XR flight simulator was prototyped using Unreal Engine 5.1; (iii) physiological measurements were omitted due to the risk of expanding the study's scope too much; (iv) lastly, to say how much CS the simulator users at FLSC can expect, we look at the SSQ Total Score (TS) of our study. In VR the mean was 15.6 and in MR 12.6 after a 30-minute, relatively calm, flight session. As discussed in Section 8.1, we argue this is *minimal* to *significant* CS elicited.

8.6 Implications

The results of our study can inform FLSC, and others, in their decisions and designs of XR applications. With MR likely being a better option for reducing Cybersickness (CS). The results also shows that CS in MR using VST is different from CS in MR using OST technology. Which is something that research needs to distinguish between when conducting and reporting on CS in MR.

8.7 Limitations and Future Research

Our study has two chief limitations. Firstly, the sample size may have been too small, as statistical significance was not reached in several statistical methods. A sample size of at least 15 was recommended by Caserman et al. [8] and around 70 by Lawson and Stanney [38]. Our study used data from 29 and recommends future research to aim for the higher sample size of 70. The sample is also very population specific and may suffer from biases by asking for voluntary participants. Therefore, the study is conservative about making general claims. Secondly, our pre-study revealed that CS can be affected by many varying factors and due to time constraints we could not design the study to control for all variables. However, this could be an objective for future research. By identifying which of these factors causes less severe CS, in MR, we would know what to design for to mitigate CS. Future research should also corroborate the findings of our study in other contexts, with other stimuli and equipment.

8.8 Conclusions

Less severe Cybersickness can seemingly be expected in Mixed Reality when compared to a Virtual Reality flight simulator and disorientation is likely the predominant Cybersickness symptoms for the Mixed Reality flight simulator. Disorientation symptoms seems to be the predominant for Virtual Reality as well, consistent with previous research.

However, it is important to emphasize that the findings from our study may not necessarily generalize broadly and should be considered within the following context: (i) the stimulus was a flight simulator with user-controlled aircraft steering; (ii) the "Varjo XR-3" eXtended Reality Head-Mounted Display was utilized; (iii) in Mixed Reality the cockpit and user's body was represented by a Video See-Through part of the real world, which was an office room, while in Virtual Reality there was no body representation; (iv) the user only interacted with a physical throttle and stick in both flight simulators; and (v) the sample was predominantly male, averaging 40 years of age with moderate experience of using flight simulators.

ACKNOWLEDGMENTS

Thanks to my supervisors Björn Thuresson and Rogier Woltjer, to all the good people at FLSC who helped with the thesis and welcoming me to their office space, and to all the people who participated in the study. Special thanks to my technical supervisor Robin Dahlkvist for always being available to bounce ideas with. Much love and thanks to my family and parents Maria Lindberg and Kenneth Bengtsson for supporting me during my studies!

REFERENCES

[1] Ahmed Alnagrat, Rizalafande Che Ismail, Syed Zulkarnain Syed Idrus, and Rawad Mansour Abdulhafith Alfaqi. 2022. A Review of Extended Reality (XR) Technologies in the Future of Human Education: Current Trend and Future Opportunity. *Journal of Human Centered Technology* 1, 2 (Aug. 2022), 81–96. https://doi.org/10.11113/humentech.v1n2.27 Number: 2.

[2] Christopher Andrews, Michael K. Southworth, Jennifer N. A. Silva, and Jonathan R. Silva. 2019. Extended Reality in Medical Practice. *Current Treatment Options in Cardiovascular Medicine* 21, 4 (March 2019), 18. https://doi.org/10.1007/s11936-019-0722-7

[3] Pauline Bimberg, Tim Weissker, and Alexander Kulik. 2020. On the Usage of the Simulator Sickness Questionnaire for Virtual Reality Research. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, Atlanta, GA, USA, 464–467. 978-1-72816-532-5 https://doi.org/10.1109/VRW50115.2020.00098

[4] Jelte E. Bos, Cyriel Diels, and Jan L. Souman. 2022. Beyond Seasickness: A Motivated Call for a New Motion Sickness Standard across Motion Environments. *Vibration* 5, 4 (Dec. 2022), 755–769. https://doi.org/10.3390/vibration5040044 Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[5] Jelte E. Bos and Ben D. Lawson. 2021. Chapter 4: Symptoms and Measurement. In *Guidelines for Mitigating Cybersickness in Virtual Reality Systems. Peer-Reviewed Final Report of the Human Factors and Medicine Panel/Modeling & Simulations Group, Activity Number 323, NATO*

STO-TR-HFM-MSG-323. NATO Science and Technology Office, BP 25, F-92201 Neuilly-sur-Seine Cedex, France. https://doi.org/10.14339/STO-TR-HFM-MSG-323

[6] Jelte E. Bos, Ben D. Lawson, Jonathan Allsop, Paolo Rigato, and Stefano Secci. 2021. Chapter 2: Introduction. In *Guidelines for Mitigating Cybersickness in Virtual Reality Systems. Peer-Reviewed Final Report of the Human Factors and Medicine Panel/Modeling & Simulations Group, Activity Number 323, NATO STO-TR-HFM-MSG-323*. NATO Science and Technology Office, BP 25, F-92201 Neuilly-sur-Seine Cedex, France. https://doi.org/10.14339/STO-TR-HFM-MSG-323

[7] Jelte E. Bos, Scott N. MacKinnon, and Anthony Patterson. 2005. Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View. *Aviation, Space, and Environmental Medicine* 76, 12 (Dec. 2005), 1111–1118. https://www.researchgate.net/profile/Scott-Mackinnon-3/publication/7401207_Motion_Sickness_Symptoms_in_a_Ship_Motion_Simulator_Effects_of_Inside_Outside_and_No_View/links/59f983d00f7e9b553ec0e21d/Motion-Sickness-Symptoms-in-a-Ship-Motion-Simulator-Effects-of-Inside-Outside-and-No-View.pdf

[8] Polona Caserman, Augusto Garcia-Agundez, Alvar Gámez Zerban, and Stefan Göbel. 2021. Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality* 25, 4 (Dec. 2021), 1153–1170. https://doi.org/10.1007/s10055-021-00513-6

[9] Cesium GS. 2023. Cesium for Unreal. https://cesium.com/platform/cesium-for-unreal/

[10] Eunhee Chang, Hyun Taek Kim, and Byounghyun Yoo. 2020. Virtual Reality Sickness: A Review of Causes and Measurements. *International Journal of Human–Computer Interaction* 36, 17 (Oct. 2020), 1658–1682. https://doi.org/10.1080/10447318.2020.1778351 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/10447318.2020.1778351.

[11] Jacob Cohen. 1988. *Statistical power analysis for the behavioral sciences* (2nd ed.). L. Erlbaum Associates, Hillsdale, N.J. 978-0-8058-0283-2

[12] Jamie Ian Cross, Christine Boag-Hodgson, Tim Ryley, Timothy Mavin, and Leigh Ellen Potter. 2022. Using Extended Reality in Flight Simulators: A Literature Review. *IEEE Transactions on Visualization and Computer Graphics* (2022), 1–1. https://doi.org/10.1109/TVCG.2022.3173921 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[13] Robin Dahlkvist. 2023. *An Evaluative Study on the Impact of Immersion and Presence for Flight Simulators in XR*. Master's thesis. KTH - Royal Institute of Technology. Issue 2023:578. https://kth.diva-portal.org/smash/get/diva2:1793349/FULLTEXT01.pdf

[14] Simon Davis, Keith Nesbitt, and Eugene Nalivaiko. 2014. A Systematic Review of Cybersickness. In *Proceedings of the 2014 Conference on Interactive Entertainment (IE2014)*. Association for Computing Machinery, New York, NY, USA, 1–9. 978-1-4503-2790-9 https://doi.org/10.1145/2677758.2677780

[15] Benj Edwards. 2015. Unraveling The Enigma Of Nintendo's Virtual Boy, 20 Years Later. https://www.fastcompany.com/3050016/unraveling-the-enigma-of-nintendos-virtual-boy-20-years-later

[16] Epic Games. 2023. Unreal Engine | The most powerful real-time 3D creation tool. https://www.unrealengine.com/en-US

[17] FOI. 2022. FLSC. https://www.foi.se/en/foi/research/aeronautics-and-space-issues/flsc.html

[18] Jann Philipp Freiwald, Yvonne Göbel, Fariba Mostajeran, and Frank Steinicke. 2020. The cybersickness susceptibility questionnaire: predicting virtual reality tolerance. In *Proceedings of Mensch und Computer 2020 (MuC '20)*. Association for Computing Machinery, New York, NY, USA, 115–118. 978-1-4503-7540-5 https://doi.org/10.1145/3404983.3410022

[19] John F Golding. 1998. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain Research Bulletin* 47, 5 (Nov. 1998), 507–516. https://doi.org/10.1016/S0361-9230(98)00091-4

[20] John F. Golding. 2006. Motion sickness susceptibility. *Autonomic Neuroscience* 129, 1 (Oct. 2006), 67–76. https://doi.org/10.1016/j.autneu.2006.07.019

[21] Marion A. Hersh. 2000. The Ethics of Military Work: A Guide for Scientists and Engineers. *IFAC Proceedings Volumes* 33, 8 (May 2000), 95–106. https://doi.org/10.1016/S1474-6670(17)35428-9

[22] HTC. 2023. SteamVR Base Station 2.0 | VIVE United States. https://www.vive.com/us/accessory/base-station2/

[23] Claire L. Hughes, Cali Fidopiastis, Kay M. Stanney, Peyton S. Bailey, and Ernesto Ruiz. 2020. The Psychometrics of Cybersickness in Augmented Reality. *Frontiers in Virtual Reality* 1 (2020), 602954. https://doi.org/10.3389/frvir.2020.602954

[24] David M. Johnson. 2005. *Introduction to and Review of Simulator Sickness Research*. Final 1832. U.S. Army Research Institute, Fort Rucker AL. 70 pages. https://apps.dtic.mil/sti/citations/ADA434495 Section: Technical Reports.

[25] JSBSim-Team. 2023. GitHub - JSBSim-Team/jsbsim: An open source flight dynamics & control software library. https://github.com/JSBSim-Team/jsbsim

[26] Mara Kaufeld, Martin Mundt, Sarah Forst, and Heiko Hecht. 2022. Optical see-through augmented reality can induce severe motion sickness. *Displays* 74 (Sept. 2022), 102283. https://doi.org/10.1016/j.displa.2022.102283

[27] Andras Kemeny, Jean-Rémy Chardonnet, and Florent Colombet. 2020. *Getting Rid of Cybersickness: In Virtual Reality, Augmented Reality, and Simulators*. Springer International Publishing, Cham. 978-3-030-59341-4 978-3-030-59342-1 https://doi.org/10.1007/978-3-030-59342-1

[28] Robert S. Kennedy, Julie Drexler, and Robert C. Kennedy. 2010. Research in visually induced motion sickness. *Applied Ergonomics* 41, 4 (July 2010), 494–503. https://doi.org/10.1016/j.apergo.2009.11.006

[29] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (July 1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3 Publisher: Taylor & Francis _eprint: https://doi.org/10.1207/s15327108ijap0303_3.

[30] Behrang Keshavarz and Heiko Hecht. 2011. Validating an Efficient Method to Quantify Motion Sickness. *Human Factors* 53, 4 (Aug. 2011), 415–426. https://doi.org/10.1177/0018720811403736 Publisher: SAGE Publications Inc.

[31] Behrang Keshavarz, Brandy Murovec, Niroshica Mohanathas, and John F. Golding. 2023. The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ): Estimating Individual Susceptibility to Motion Sickness-Like Symptoms When Using Visual Devices. *Human Factors*

65, 1 (Feb. 2023), 107–124. https://doi.org/10.1177/00187208211008687 Publisher: SAGE Publications Inc.

[32] Behrang Keshavarz, Raheleh Saryazdi, Jennifer L. Campos, and John F. Golding. 2019. Introducing the VIMSSQ: Measuring susceptibility to visually induced motion sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 63, 1 (Nov. 2019), 2267–2271. https://doi.org/10.1177/1071181319631216

[33] Hyun K. Kim, Jaehyun Park, Yeongcheol Choi, and Mungyeong Choe. 2018. Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment. *Applied Ergonomics* 69 (May 2018), 66–73. https://doi.org/10.1016/j.apergo.2017.12.016

[34] Jiwon Kim and Taezoon Park. 2020. Investigation of Factors Influencing Simulator Sickness and the Sense of Presence in Flight Simulator. https://doi.org/10.24507/icicelb.11.05.463

[35] Ramy Kirollos, Wasim Merchant, and Tania Randall. 2022. *Comparing cybersickness in two levels of virtuality in a mixed reality head-mounted display*. Scientific Report DRDC-RDDC-2022-R158. Toronto Research Centre Defence Research and Development Canada, Toronto, Canada. 33 pages. https://cradpdf.drdc-rddc.gc.ca/PDFS/unc405/p815726_A1b.pdf

[36] Tim Laudien, Johannes Maria Ernst, and Bianca Isabella Schuchardt. 2022. Implementing a Customizable Air Taxi Simulator with a Video-See-Through Head-Mounted Display – A Comparison of Different Mixed reality Approaches. In *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. IEEE, Portsmouth, VA, USA, 1–10. 978-1-66548-607-1 https://doi.org/10.1109/DASC55683.2022.9925870 ISSN: 2155-7209.

[37] Joseph J. LaViola. 2000. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin* 32, 1 (Jan. 2000), 47–56. https://doi.org/10.1145/333329.333344

[38] Ben Lawson and Kay Stanney. 2021. Editorial: Cybersickness in Virtual Reality and Augmented Reality. *Frontiers in Virtual Reality* 2 (Oct. 2021), 759682. https://doi.org/10.3389/frvir.2021.759682

[39] Ben D. Lawson, Paolo Prioretti, Oleksandr Burov, Peder Sjölund, Timothy Rodabaugh, Ramy Kirollos, and Marten Bloch. 2021. Chapter 5: Factors Impacting Cybersickness. In *Guidelines for Mitigating Cybersickness in Virtual Reality Systems. Peer-Reviewed Final Report of the Human Factors and Medicine Panel/Modeling & Simulations Group, Activity Number 323, NATO STO-TR-HFM-MSG-323.* NATO Science and Technology Office, BP 25, F-92201 Neuilly-sur-Seine Cedex, France. https://doi.org/10.14339/STO-TR-HFM-MSG-323

[40] Paolo Leoncini, Ben D. Lawson, John French, Jelte E. Bos, Oleksandr Burov, and Dave Clement. 2021. Chapter 6: Mitigation Methods. In *Guidelines for Mitigating Cybersickness in Virtual Reality Systems. Peer-Reviewed Final Report of the Human Factors and Medicine Panel/Modeling & Simulations Group, Activity Number 323, NATO STO-TR-HFM-MSG-323.* NATO Science and Technology Office, BP 25, F-92201 Neuilly-sur-Seine Cedex, France. https://doi.org/10.14339/STO-TR-HFM-MSG-323

[41] Wasim Merchant and Ramy Kirollos. 2022. *An Overview of Cybersickness Self-Report Measures for use in Defence Research and Development Canada Experiments*. Technical Report DRDC-RDDC-2022-D063. Defence Research and Development Canada. https://cradpdf.drdc-rddc.gc.ca/PDFS/unc392/p814963_A1b.pdf

[42] Ines Miguel-Alonso, Bruno Rodriguez-Garcia, David Checa, and Andres Bustillo. 2023. Countering the Novelty Effect: A Tutorial for Immersive Virtual Reality Learning Environments. *Applied Sciences* 13, 1 (Jan. 2023), 593. https://doi.org/10.3390/app13010593 Number: 1 Publisher: Multidisciplinary Digital Publishing Institute.

[43] Paul Milgram and Fumio Kishino. 1994. A Taxonomy of Mixed Reality Visual Displays. *IEICE Transactions on Information Systems* E77-D, 12 (Dec. 1994), 1321–1329. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f78a31be8874eda176a5244c645289be9f1d4317

[44] NATO Science and Technology Office. 2021. *Guidelines for Mitigating Cybersickness in Virtual Reality Systems*. Peer-reviewed Final Technical Report of the Human Factors and Medicine / Modeling Simulations Group, Activity Number 323. NATO STO-TR-HFM-MSG-323. NATO STO, BP 25, F-92201 Neuilly-sur-Seine Cedex, France. 194 pages. https://doi.org/10.14339/STO-TR-HFM-MSG-323

[45] Sean Pooley. 2023. When Virtual Reality Started – A Complete History of VR. https://vrinformers.com/when-virtual-reality-started-a-complete-history-of-vr/

[46] Jerrold D. Prothero. 1998. *The Role of Rest Frames in Vection, Presence and Motion Sickness*. PhD. University of Washington, HIT-Lab. http://cumincad.scix.net/cgi-bin/works/Show?diss_prothero

[47] J. T. Reason and J. J. Brand. 1975. *Motion sickness*. Academic Press, Oxford, England. 978-0-12-584050-7 Pages: vii, 310.

[48] Gary E. Riccio and Thomas A. Stoffregen. 1991. An ecological Theory of Motion Sickness and Postural Instability. *Ecological Psychology* 3, 3 (Sept. 1991), 195–240. https://doi.org/10.1207/s15326969eco0303_2 Publisher: Routledge _eprint: https://doi.org/10.1207/s15326969eco0303_2.

[49] Austin Rooney. 2016. 160624-N-RT381-040. https://commons.wikimedia.org/wiki/File:160624-N-RT381-040_(27638458190).jpg

[50] Dimitrios Saredakis, Ancret Szpak, Brandon Birckhead, Hannah A. D. Keage, Albert Rizzo, and Tobias Loetscher. 2020. Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and Meta-Analysis. *Frontiers in Human Neuroscience* 14 (2020), 96. https://doi.org/10.3389/fnhum.2020.00096

[51] Kay Stanney, Ben D. Lawson, Bas Rokers, Mark Dennison, Cali Fidopiastis, Thomas Stoffregen, Séamas Weech, and Jacqueline M. Fulvio. 2020. Identifying Causes of and Solutions for Cybersickness in Immersive Technology: Reformulation of a Research and Development Agenda. *International Journal of Human–Computer Interaction* 36, 19 (Nov. 2020), 1783–1803. https://doi.org/10.1080/10447318.2020.1828535 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/10447318.2020.1828535.

[52] Kay M. Stanney and Robert S. Kennedy. 1997. The psychometrics of cybersickness. *Commun. ACM* 40, 8 (Aug. 1997), 66–68. https://doi.org/10.1145/257874.257889

[53] Kay M. Stanney, Robert S. Kennedy, and Julie M. Drexler. 1997. Cybersickness is Not Simulator Sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 41, 2 (Oct. 1997), 1138–1142. https://doi.org/10.1177/107118139704100292 Publisher: SAGE Publications Inc.

[54] Nana Tian, Phil Lopes, and Ronan Boulic. 2022. A review of cybersickness in head-mounted displays: raising attention to individual susceptibility. *Virtual Reality* 26, 4 (Dec. 2022), 1409–1441. https://doi.org/10.1007/s10055-022-00638-2

[55] Michel Treisman. 1977. Motion Sickness: An Evolutionary Hypothesis. *Science* 197, 4302 (July 1977), 493–495. https://doi.org/10.1126/science.301659 Publisher: American Association for the Advancement of Science.

[56] Kathleen Van Benthem, Heather Cobert, Richard Zobarich, and Calian Ltd. 2021. *Human Factors and Ergonomics Considerations when using Augmented Reality Head Mounted Displays—Literature Analysis Report*. Technical Report DRDC-RDDC-2021-C198. Defence Research and Development Canada, Ottawa, (ON) Canada. 130 pages. https://cradpdf.drdc-rddc.gc.ca/PDFS/unc370/p813712_A1b.pdf

[57] Varjo. 2020. Varjo XR-3 - The industry's highest resolution mixed reality headset | Varjo. https://varjo.com/products/xr-3/

[58] Wikipedia. 2023. Meta Quest 2. https://en.wikipedia.org/w/index.php?title=Meta_Quest_2&oldid=1143770250 Page Version ID: 1143770250.

[59] XR Collaboration. 2021. XR Glossary. https://xrcollaboration.com/guide/a-global-resource-guide-to-xr-collaboration/xr-glossary/

A APPENDICES

A.1 Table of cybersickness symptoms

Table 9: List of 34 symptoms of cybersickness. (•) marks grouping according to column. (?) marks unknown/desputed grouping. Adapted from Table 4-1 in [5].

Symptom	Well-Established	Neuro-physiologic	Psycho-logic
Annoyed/irritated			•
Apathy/boredom/indifference			•
Blurred vision / difficulty focusing	•	•	
Burping	•	•	
Depression (mental)	•		•
Desire to move bowels		?	?
Difficulty concentrating / fuzzy / foggy headed	•		•
Disorientation	•	•	?
Dizziness	•	•	
Drowsiness	•	•	
Eyestrain	•	•	?
Faintness / light-headedness	•		•
Fatigue/tiredness/lethargy/weakness/lassitude	•	?	•
Feeling warm or cold	•	?	
Flatulence	•	•	
Flushing		•	
Gastrointestinal activity and/or belly sounds		•	
Headache	•	?	?
Introversion			•
Lack of appetite	•	?	?
Lack of motivation			•
Nausea	•	•	?
Pallor	•	•	
Postural instability / feeling uneasy		•	
Relaxation		?	?
Retching	•	•	
Salivation (usually increased; occasionally decreased)	•	•	
Stomach or epigastric awareness or discomfort[a]	•	•	
Stuffy feeling in the head / fullness of head	•		•
Sweating (cold sweating)	•	•	
Uneasy/general discomfort			•
Vertigo[b]	•	•	
Vomiting	•	•	
Yawning	•	•	

[a] Stomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea.
[b] Vertigo is experienced as loss of orientation with respect to vertical upright.

A.2 Figure showing the final head-down display and checkpoint

(a) The HDD. Left: Flight instructions in Swedish. Center: Map and flight data. Right: Sickness rating in Swedish

(b) A checkpoint in the terrain

Figure 16: The head-down display and checkpoint

A.3 Table of Varjo XR-3 technical specifications of maximum capability

Table 10: Technical specifications of the Varjo XR-3 head-mounted display

Varjo XR-3 Technical Specifications	
Display	Full Frame Bionic Display. Peripheral: 2 x LCD binocular. Focal: 2 x uOLED. Colors: 99% sRGB, 93% DCI-P3.
Refresh rate	90 Hz
Resolution	Peripheral area at over 30 PPD, 2880 x 2720 px per eye. Focal area at 70 PPD, 1920 x 1920 px per eye.
Field of view	115° horizontal; 90° vertical Focal displays: 27°
Optics	Aspherical lenses
MR VST	Dual 12MP cameras at 90 Hz
XR Depth	LiDAR + RGB fusion, 40 cm – 5 cm operating range
Positional tracking	SteamVR 2.0 at 100 Hz tracking speed.
Hand Tracking	Ultraleap Gemini (v5)
Eye tracking	200 Hz with sub-degree accuracy
IPD	Automatic hardware adjustment 59-71 mm
Weight	980 gram including head-strap