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STO TECHNICAL REPORT **TR-HFM-MSG-323**

Guidelines for Mitigating Cybersickness in Virtual Reality Systems

(Guide d'atténuation du cybermalaise dans les systèmes de réalité virtuelle)

Peer-reviewed Final Technical Report of the Human Factors and Medicine / Modeling Simulations Group, Activity Number 323. This Report describes the outcome of the activity performed during the study.

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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List of Acronyms

AR	Augmented Reality
ATF	Anatomical Transfer Function
BCE	Before the Common Era
BCV	Bone Conducted Vibration
CAVE	Cave Automated Virtual Environment
CBT	Cognitive Behavioural Therapy
CGI	Computer Generated Image
CNS	Central Nervous System
COE	Centre of Excellence
COTS	Commercial Off The Shelf
CS	Cyber Sickness
DoD	Department of Defence
DOF	Degree Of Freedom
EEG	Electro Encephalo Graphy
ET	Exploratory Team
FDA	Food And Drug Administration
FMS	Fast Motion Sickness Scale
FoV	Field of View
GVS	Galvanic Vestibular Stimulation
HFM	Human Factor and Medicine
HMD	Head Mounted Display
HRTF	Head-Related Transfer Function
IOD	Interocular Distance
IPD	Interpupillary Distance
ISS	International Space Station
IVAS	Integrated Visual Augmentation System
LCD	Liquid Crystal Display
M&S	Modelling and Simulation
MHQ	Motion History Questionnaire
MILMED	Military Medicine
MISC	MIsery SCale
MR	Mixed Reality
MS	Motion Sickness
MSAQ	Motion Sickness Assessment Questionnaire
MSG	Modelling and Simulation Group
MSI	Motion Sickness Incidence
MSQ	Motion Sickness Questionnaire
MSSQ	Motion Sickness Susceptibility Questionnaire

NMSMP	NATO Modelling and Simulation Master Plan
PDC	Pensacola Diagnostic Criteria
PDL	Polarization-Dependent Lenses
PONV	Postoperative Nausea and Vomiting
PPI	Pixels Per Inch
RTG	Research Task Group
SSQ	Simulator Sickness Questionnaire
ST	Specialists Team
STO	Science and Technology Organisation
TDCS	Transcranial Direct Current Stimulation
UI	User Interface
UTSA	University of Texas at San Antonio
V&V	Verification and Validation
VE	Virtual Environment
VI	Vomiting Incidence
VIMS	Visually Induced Motion Sickness
VIMSSQ	Visually-Induced Motion Sickness Questionnaire
VR	Virtual Reality
VRSQ	Virtual Reality Sickness Questionnaire
XR	eXtended Reality

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Guidelines for Mitigating Cybersickness in Virtual Reality Systems

(STO-TR-HFM-MSG-323)

Executive Summary

Cybersickness is discomfort that users experience during or after a session in a synthetic environment; it is similar to motion or simulator sickness. It is a pervasive problem in military synthetic environment-based training such as occurs in flight simulators, combat vehicle driving simulators, and immersive or Virtual Reality (VR) simulations of dynamic infantry squad maneuvers. Cybersickness can discourage synthetic environment-based training, reducing the efficiency and safety of training. Moreover, it can be a barrier to the adoption of Virtual Reality (VR), thus limiting the dissemination of improved training or rehabilitation tools.

A Specialist Team (ST) was formed on "Guidelines for Mitigating Cybersickness in Virtual Reality Systems," as part the NATO HFM-MSG-323 Human Factors and Medicine (HFM) and Modelling and Simulation Group (MSG). The aim of the ST was to identify the best practices, design techniques, and other procedures or countermeasures that are likely to reduce the prevalence or severity of cybersickness while using VR goggles and related devices. This was done by reviewing and discussing the scientific literature on cybersickness, with a focus on applications in defence. As cybersickness studies are limited, inferences were drawn from simulator sickness and related maladies.

The literature was assessed concerning the causes and prevalence of cybersickness (Chapter 2), the known symptoms and measures of cybersickness (Chapter 4), and the factors that elicit cybersickness (Chapter 5). Individual (Section 5.1), technological (Section 5.2) and operational (Section 5.3) factors were studied which increase or decrease cybersickness. Via narrative synthesis of the literature, many ST discussions of the findings, and peer comments by some outside Reviewers (p. x), the ST identified the most scientifically justified contributors to cybersickness, as well as the most proven countermeasures, which are presented as guidelines for mitigating cybersickness for defence use cases (Chapter 7).

To enhance training by improving decisions concerning when to introduce helpful targeted interventions or preventative measures, recommendations are provided concerning individual characteristics which are most likely to predispose a trainee to cybersickness (Section 5.1). However, even the most promising individual predictors require more research prior to their usage to aid personnel selection decisions).

Operational recommendations for preventing cybersickness (Section 5.3; Chapter 7) are discussed in this report; they relate to procedural interventions to enhance the design of specific training scenarios and are subdivided into three phases comprising operational considerations before, during, and after the usage of VR goggles (Section 7.3). In addition, recommendations have been identified for the design phase of VR systems, which include technological aspects of the VR equipment (Sections 6.1 and 7.3). Finally (Section 6.2), emerging behavioral, neurophysiological, and design methods to mitigate cybersickness are presented which require further investigation and validation before their application in defence settings.

A research gap identified in this report is that as Augmented Reality (AR) and Mixed Reality (MR) become more widely endorsed for military training and operations, expanded investigations of cybersickness in AR and MR goggles will be necessary to understand their limitations, capabilities, and best use cases. The identified knowledge gaps and emerging findings in literature contributed to the ST's recommended future R&D activities to resolve cybersickness (Chapter 8), some of which might be addressed in new studies within the NATO STO framework.

Guide d’atténuation du cybermalaise dans les systèmes de réalité virtuelle

(STO-TR-HFM-MSG-323)

Synthèse

Le cybermalaise est un inconfort que les utilisateurs ressentent pendant ou après une séance dans un environnement synthétique ; il est semblable au mal des transports ou au mal de simulateur. Il s’agit d’un problème omniprésent dans l’entraînement basé sur les environnements synthétiques, tels que les simulateurs de vol, les simulateurs de conduite de véhicules de combat et les simulations immersives ou en réalité virtuelle (VR) des manœuvres dynamiques des équipes d’infanterie. Le cybermalaise peut décourager l’entraînement basé sur les environnements synthétiques, réduisant ainsi l’efficacité et la sécurité de la formation. De plus, il peut être un obstacle à l’adoption de la réalité virtuelle, ce qui limite la diffusion des outils améliorés d’entraînement ou de réadaptation.

Une équipe spécialisée (ST) intitulée « Guide d’atténuation du cybermalaise dans les systèmes de réalité virtuelle » a été constituée dans le cadre du HFM-MSG-323 de la Commission sur les facteurs humains et la médecine et du groupe OTAN sur la modélisation et la simulation (MSG). Le but de cette ST était d’identifier les meilleures pratiques et de concevoir des techniques et autres procédures ou contre-mesures susceptibles de réduire la prévalence ou la gravité du cybermalaise pendant l’utilisation de casques de VR et de dispositifs apparentés. Pour cela, l’équipe a passé en revue et discuté de la littérature scientifique sur le cybermalaise, en se concentrant sur les applications dans le domaine de la défense. Les études sur le cybermalaise étant limitées, le mal de simulateur et les maux liés ont servi de base à des déductions.

La littérature a été évaluée sur les sujets suivants : causes et prévalence du cybermalaise (chapitre 2), symptômes connus et mesures du cybermalaise (chapitre 4) et facteurs qui provoquent le cybermalaise (chapitre 5). Les facteurs individuels (5.1), technologiques (5.2) et opérationnels (5.3) qui augmentent ou diminuent le cybermalaise ont été étudiés. À l’aide d’une synthèse narrative de la littérature, des nombreuses discussions de la ST sur les conclusions et des commentaires de quelques pairs évaluateurs externes (p. x), la ST a identifié les facteurs de cybermalaise les plus justifiés sur le plan scientifique, ainsi que les contre-mesures ayant le plus fait leurs preuves, et les présente sous la forme d’un guide d’atténuation du cybermalaise pour les cas d’utilisation en défense (chapitre 7).

Dans le but de favoriser la formation en choisissant plus judicieusement quand introduire des interventions ciblées utiles ou des mesures de prévention, la ST fournit des recommandations sur les caractéristiques individuelles les plus susceptibles de prédisposer un participant au cybermalaise (paragraphe 5.1). Néanmoins, même les variables prédictives individuelles les plus prometteuses nécessitent plus de recherches avant d’être utilisées pour faciliter la sélection du personnel.

Le présent rapport discute de recommandations opérationnelles pour prévenir le cybermalaise (paragraphe 5.3 et chapitre 7). Ces recommandations portent sur des procédures visant à améliorer la conception de scénarios d’entraînement particuliers et sont divisées en trois phases chronologiques et opérationnelles, à savoir avant, pendant et après l’utilisation de casques de VR (7.3). Par ailleurs, le rapport émet des recommandations pour la phase de conception des systèmes de VR, qui incluent des aspects technologiques de l’équipement de VR (paragraphes 6.1 et 7.3). Pour finir (6.2), nous présentons des méthodes comportementales, neurophysiologiques et de conception visant à atténuer le cybermalaise, lesquelles nécessitent encore des études et une validation avant d’être appliquées à la défense.

Ce rapport identifie une lacune : avec l’utilisation croissante de la réalité augmentée (AR) et de la réalité mixte (MR) dans les formations et les opérations militaires, il faudra élargir les recherches sur le cybermalaise dû aux casques d’AR et de MR, pour comprendre les limites, les capacités et les meilleurs cas d’utilisation de ces équipements. Les lacunes en matière de connaissances et les conclusions émergentes de la littérature ont contribué aux activités de R&D recommandées par la ST pour remédier au cybermalaise (chapitre 8), certaines d’entre elles pouvant faire l’objet de nouvelles études dans le cadre de la STO de l’OTAN.

Chapter 1 – HFM-MSG-323 STUDY

Paolo Proietti[1]

1.1 INTRODUCTION

In the natural environment, one's brain must integrate real-time visual, auditory, vestibular, somatosensory, and other inputs to produce a compelling feeling of immersion and to ensure normal coordination. In the past decade, there has been a rapid advance in immersive Virtual Reality (VR) displays which are restricted mainly to visual and auditory senses in bimodal interactions. A problem with VR is that users develop symptoms similar to motion sickness – a malady called cybersickness.

The discomfort that users experience during or after a session in a synthetic environment became widely known in the military setting during the advent of flight simulators. The related phenomenon of simulator sickness can discourage pilots from using flight simulators, reduce the efficiency of training (through distraction and the encouragement of adaptive behaviours that are unfavourable for performance, such as limiting head movements associated with visual search), or compromise safety when sick or disoriented pilots leave the simulator (e.g., to operate ground vehicles whilst in a disoriented state). In a similar manner, cybersickness can be a barrier to using VR for military applications, and thereby limit the dissemination of improved training or rehabilitation tools.

1.2 SCOPE AND RATIONALE

The NATO STO HFM-MSG-323 Study intends to review the factors contributing to sickness that are associated with the individual (e.g., history of susceptibility), the VR system (e.g., system lag), and the task (e.g., type of virtual locomotion control). Solutions to reduce symptoms of cybersickness were identified, such as earth-referenced cues and exposure limits. These can be implemented during system design and usage and can aid in the management and treatment of cybersickness. Adoption of the guidelines in this report for mitigating cybersickness will enhance training effectiveness throughout the military community through better implementation of VR [1].

The Study findings are summarized in this report which is intended to be provide "Guidelines for Mitigating Cybersickness in Virtual Reality Systems", the adoption of which will enhance training effectiveness within the overall military community through increased standardization of the characteristics of VR systems and their usage. The rationale for this Study come also from the outcome of the MSG-ET-050 on "Standards for xR[2] (Virtual, Augmented and Mixed Reality)" which asserts the cybersickness aspects of xR are not yet covered by any existing standard [2]. Finally, the HFM-297 RTG on "Assessment of Augmentation Technologies for Improving Human Performance" addresses the cybersickness as a relevant effect on using VR technology [3].

1.3 PURPOSE

The aim of the Study is to identify the best practice and design techniques and measures that may reduce the occurrence of cybersickness, taking into consideration the literature and the experience and competences of

[1] To cite: Proietti, P., (2021). HFM-MSG-323 Study. 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, Chapter 1.

[2] Extended Reality.

the Study Members, among whom were human factor experts, physicians, and virtual reality systems designers.

The overarching aim of this report is to give scientifically based guidelines on how to mitigate cybersickness, with a focus on immersive virtual environments (and VR goggles in particular) as they are used in the defence setting. To generate useful guidelines, a proper understanding of the problem is necessary. To that end, this report will:

1) Give background information about cybersickness (observations, theories, taxonomy) (Chapter 2).
2) Give an overview of and explain the different definitions related to cybersickness and the technology in which cybersickness occurs (Chapter 3).
3) Explain cybersickness in terms of symptoms and how it can be measured (Chapter 4).
4) Give an overview of all factors known to affect cybersickness (Chapter 5).
5) Give an overview of proven and suggested countermeasures (Chapter 6).
6) Give guidelines, based on suggestions and recommendations, about the usage of virtual reality-based systems for minimizing the cybersickness impact (Chapter 7).
7) Give an overview of unsolved issues requiring further elaboration (Chapter 8).

1.4 DISCLAIMER

The HFM-MSG-323 Team and their nations do not endorse or recommend any commercial products, processes, medical treatments, or services. Therefore, reference in this report to any specific commercial products, process, medical treatments, or services by trade name, trademark, manufacturer, or otherwise, cannot be construed as an endorsement, recommendation, or preference by the NATO or Nations or Authors' Organizations, and any failure to mention a particular firm, commercial product or process is not a sign of disapproval.

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Any information concerning the demographics of military service members should **not** be implemented without first consulting equal opportunity and legal representatives of the Nation(s) concerned.

1.5 REFERENCES

[1] NATO STO. (2019). HFM-MSG-323 ST Guidelines for mitigating cybersickness in virtual reality systems, TAP, 11 April 2019.

[2] NATO STO. (2020). MSG-TR-ET-050 Standards for xR (virtual, augmented and mixed reality), Final Report, 2020.

[3] NATO STO. (2017). HFM-297 RTG Assessment of augmentation technologies for improving human performance, TAP, 6 Apr 2017.

Chapter 2 – INTRODUCTION

Jelte Bos, Ben D. Lawson, Jonathan Allsop, Paolo Rigato, Stefano Secci[1]

2.1 GENERALITIES

The human brain must integrate visual, auditory, vestibular, somatosensory, and other inputs to produce a feeling of immersion or presence in the natural environment. Here, there is a tendency to frame the term "immersion" in a technical context, and "presence" in a perceptual context (see Section 3.1.3). In the past decade, there has been a rapid advance in immersive Virtual Reality technology which included visual and auditory stimuli, and in some cases even rudimentary tactile or vestibular cues. A problem with VR is that the pattern of sensory interactions is often not normal, and thus users may develop symptoms similar to motion sickness, resulting in a syndrome referred to as VR sickness or, most popularly, cybersickness [1]. The discomfort experienced by users of synthetic or virtual environments became widely known by the military at the beginning of the flight simulator era and it persists today. In general, VR or Virtual Environments (VE) offer the following advantages.

- *Controllability and flexibility*: simulators can be used anywhere and anytime, mimicking any condition anywhere and anytime, different from the user location and time.
- *Safety*: Training scenarios deemed unsafe to be conducted in real life could be replicated virtually.
- *Training effectiveness*: Because interference with tasks is more feasible in a virtual than in a real environment, and tasks can hence be repeated ad libitum, training can be better optimized.
- *Cost effectiveness*: Redundant preconditions can be eliminated (e.g., no need to sail an entire ship and crew to the location of interest).[2]
- *Prototyping*: Systems and methods (new ways of training) can be evaluated in their design phase and away from unwanted spectators.
- *Green*: Simulation is generally (much) less energy demanding than real operation, also allowing for green electric powering, and avoiding redundancies as mentioned above.

The use of virtual environments is increasing. Budget cuts act as serious constraints to the use of costly equipment intended for operational use, and the gaming industry offers cheap hard- and software, while improvements are being made faster than ever before. Yet, in all these virtual environments, cybersickness remains an issue. Cybersickness not only pertains to well-being, but to human (and training) performance and economic interest as well. When using simulators for training purposes, the 50% dropout of trainees due to simulator sickness is not exceptional [2], and over 90% dropout has been reported on in certain populations [3]. At the same time, current trends in military development (automation, teleoperation, shift to a more supervising role of operators) make the deployment of VR Head Mounted Displays (HMDs) more likely in normal operations. Most people exposed to VR HMD suffer from cybersickness to some extent. Moreover, there are reasons to infer that cybersickness increases with image fidelity [4], [5]. Because image fidelity as well as the use of VR HMDs is increasing, cybersickness can be assumed to be of increasing concern. The primary focus of the current report is therefore on cybersickness occurring from the use of VR HMDs and goggles.

[1] To cite: Bos, J.E., Lawson, B.D., Allsop, J., Rigato, P., Secci, S., (2021). 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, Chapter 2.

[2] Note that safety may prevail over cost effectiveness.

The ongoing acquisition of increasingly complex (weapon) systems requires a more explicit and continually updated training strategy. Part of this need can be met by using VR technology. Unfortunately, cybersickness can discourage trainees from using VR, reduce the efficiency of training, and compromise safety due to aftereffects. Despite the growing interest in VR applications across all military domains, guidance and regulations are lacking; these are needed to ensure that military users are able to optimally benefit from these technologies while minimizing the incidence and severity of cybersickness. Employees involved with procurement of these systems as well as those involved with the development of training have expressed a desire for up-to-date guidelines that will help with this aim.

Where appropriate, the remaining report will make reference to the literature at issue. A search on the interaction between motion sickness and visual factors, as published in scientific journals, resulted in the histogram shown in Figure 2-1. From this figure, it is evident that interest in this topic is growing rapidly, due to increased use of VR equipment in general and head mounted VR in particular [6].

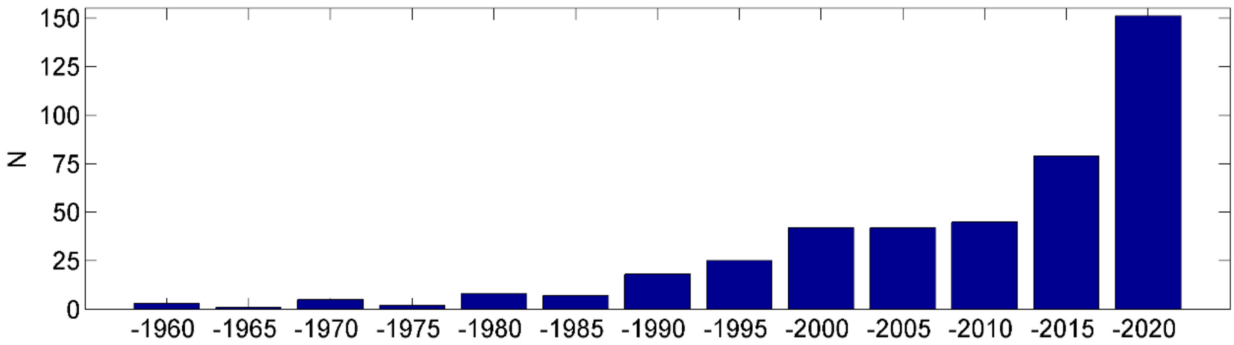

Figure 2-1: Number of Publications (N) with an Explicit Reference to the Interaction between Vision and Motion Sickness in Any Virtual Environment (1930s to December 2020).

2.1.1 Report Restrictions

Given the growing importance of VR goggles, their complete visual isolation from the real world, and high levels of sickness reported (compared to other virtual environments), the NATO Specialist Team HFM-MSG 323 chose to focus on cybersickness related to VR HMDs, or goggles in particular. Because several issues related to VR also hold for mixed and augmented reality systems, these systems will be covered as well when appropriate. This limitation does not imply the findings reported here are limited to the use of VR goggles, nor does it imply that literature on other virtual environments has been ignored, because the same principles hold for any virtual environment. As discussed above and shown in Figure 2-2, cybersickness can formally be considered a form of simulator sickness, while simulator sickness is often related to the use of flight and driving simulators. These simulators may be equipped with moving bases that are limited by a number of factors, such as the limited room in which they are based (compared to some vehicles being simulated, which can travel all over the world). This report will not address the art of incorporating the physical motions to be simulated into the motion envelope of the simulator platform (i.e., limitations regarding motion amplitudes, peak velocities, and accelerations (see Ref. [7] and Section 3.1.4).

2.2 TAXONOMY

Cybersickness is considered to be a form of motion sickness (medically referred to as kinetosis) that can be differentiated from other types as shown in Figure 2-2. In this figure, airsickness, carsickness, and seasickness overlap because they only differ with respect to the environment in which they are observed and their content of motion frequencies, amplitudes, and the (possibly highly non-linear) interactions between frequencies and degrees of motion (such as linear and angular Coriolis effects). The cause of these forms of motion sickness is predominantly physical motion. Simulator sickness is shown in a separate oval in Figure 2-2 because its cause is predominantly visual-vestibular interactions. Only a minority of simulators have a motion base, which motion then may differ (considerably) from the simulated vehicle motion (see also Section 2.3), further exacerbating sickness.

We define simulator sickness as being sickness that occurs in the simulation where it would not occur in the real condition being simulated. It is typically caused by limitations of the simulator visuals and/or moving base, which cause those stimuli to not be concordant with the real motion being simulated. Sickness caused by mere visual motion (visually induced motion sickness, VIMS) and sickness caused by digitally driven display systems are largely enclosed by the simulator sickness oval in Figure 2-2, where VR sickness and cybersickness are considered equivalent. Space sickness is shown in a separate oval because the central nervous system has to reinterpret expected inertial and gravitational accelerations in microgravity. Several symptoms associated with motion sickness can be categorized as eye strain (medically referred to as asthenopia), and these seem of particular interest with respect to cybersickness (see Chapter 4).

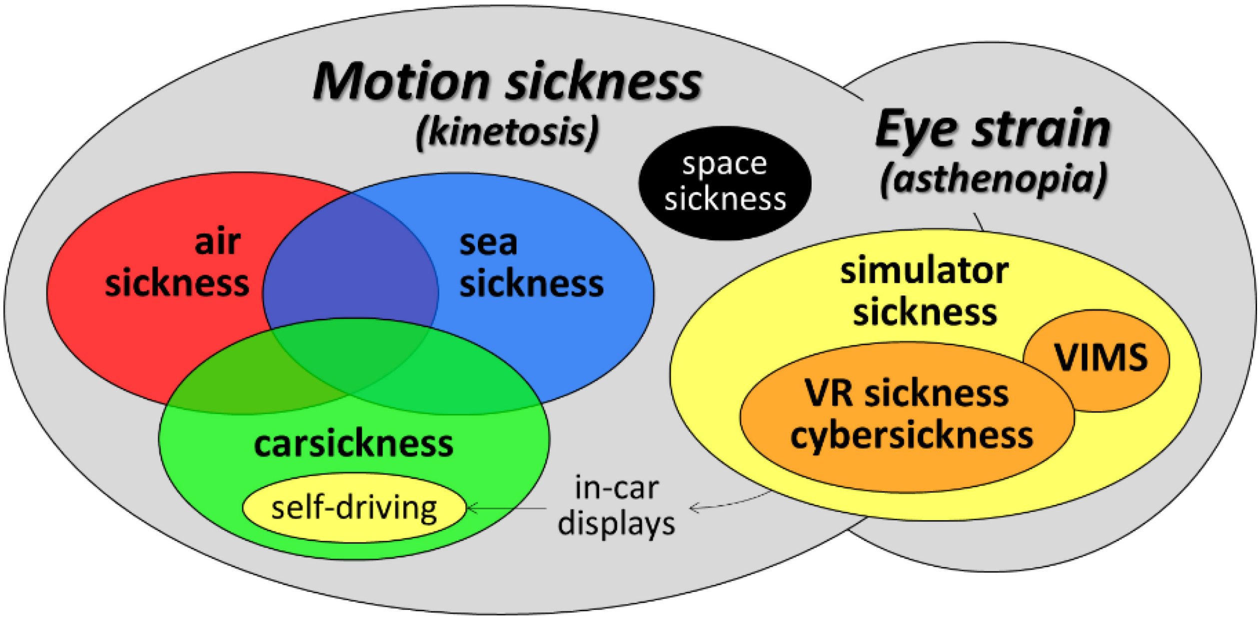

Figure 2-2: Taxonomy of Different Forms of Motion Sickness.

Eye strain may, possibly predominantly, be ascribed to what may be called visual-visual conflicts, such as accommodation-convergence conflicts, rather than to vestibular-expectation or visual-vestibular conflicts, and concerns symptoms such as blurred vision, headaches, and non-specific pupil movements. Because eyestrain may occur in conditions without any visual or physical motion, such as bright light, fatigue, wearing goggles per se, or watching a screen placed close to the eyes for a prolonged time [8], it makes sense to distinguish these from nausea and sickness. At the same time, it should be reckoned that eye strain is not specific to motion sickness, as holds for the other symptoms elaborated in Chapter 4. However, accommodation-convergence conflicts may confuse the brain with respect to depth perception, therefore, it is reasonable to assume that accommodation-convergence conflicts also contribute to the visual-vestibular conflict. Conversely, physically induced motion sickness can cause visual effects (e.g., reduced visual acuity [9], further thwarting an unambiguous separation between visual and vestibular effects). This is why Figure 2-2 makes a distinction between motion sickness and eye strain while showing an overlap. This overlap concerns simulator sickness and its sub-forms in particular, because of the essential visual contribution. It remains to be seen whether there is a need to further elaborate on and possibly solve this ambiguity. In this figure, simulator sickness was chosen as an all-encompassing term for sickness with a predominantly visual cause (e.g., visual cues indicating motion not corroborated by vestibular or tactile senses). This terminology was used for historical reasons, as flight simulators were recognized as sickening by the 1950s, and any device creating a virtual environment can be utilized as a simulator (which is the most likely military use case).

A detail concerns the fact that all forms of motion sickness considered here are caused by external or endogenous factors. Symptoms similar to motion sickness can, however, also be brought about by endogenous factors, such as dysfunction of the organs of balance and/or the central nervous system, the latter also concerning visual-vestibular interactions. Hidden anomalies may explain part of the large inter-individual variability in motion sickness susceptibility observed.

2.3 INCIDENCE OF CYBERSICKNESS

Motion sickness symptoms were reported by 61 – 80 % of the users of pre-2011 VR, with 25 – 43 % reporting nausea [10]. Evidence is sparse concerning current VR, but 33% of the subjects observed by Stone [11] said they "somewhat/strongly agree" it was nauseating to play one of three dynamic VR games for an average of 9 – 19 minutes. Davis et al. [12] found that all their subjects got at least mild nausea experiencing two VR rollercoasters (for an average of 8 – 13 minutes each), with 17% withdrawing from one simulation and 66% from the other. Most of the aforementioned evidence is derived from stimuli intentionally designed to elicit at least mild MS, so actual MS incidence may be lower in the total VR user population. Nevertheless, the limited evidence available to date implies that modern VR systems have not eliminated the possibility for sickness, and that in specific circumstances (nearly) 100% of all current viewers still do suffer in some extent. Of all VR systems available, varying from a simple computer screen, (large) cylindrical and spherical (dome) screens, caves and (moving base) simulators, HMD systems do cause most sickness, (see Ref. [13] for a review and Chapter 5). The most recent study [14] compared a screen projection system with an HMD under otherwise equal visual conditions (among which the field of view), reporting about twice as much sickness when using the HMD. This latter observation has also been a main driver for the report restrictions mentioned in Section 2.1.1.

2.4 CAUSES AND THEORIES

Motion sickness is characterized by symptoms such as drowsiness, dizziness, pallor, cold sweating, and increased salivation, which may build to nausea and vomiting (see Chapter 4). As discussed above, motion sickness affects feelings of well-being, and also task performance and safety [15], [16], [17]. Performance and safety are of particular interest in defence scenarios. Motion sickness is also related to postural instability [18], [19], which may last long after VR exposure and decreases safety [20], [21].

VIMS became a problem for the military with the introduction of flight simulators in the late 1950s. The problem reached a broader public due to computer gaming and the introduction of immersive VR using HMDs since the 2010s. Although the problem of cybersickness is often believed to be solved by new and better hardware (e.g., spatial and temporal resolution, delay, and field of view [22], the opposite is true when the equipment causes a sensory conflict [20], [5], [12]. The combination of the ensuing visual-vestibular conflict and the increasing image fidelity will collectively become greater concerns in the (near) future.

Of fundamental importance to motion sickness and cybersickness are the labyrinthine (vestibular) organs of balance. While in general blind people are susceptible to motion sickness [23], it has been known since the 19th century that many deaf-mutes are not susceptible to seasickness [24], [25]. Those cases are now explained by a total absence of vestibular function [16], [26]. It has, moreover, been shown that labyrinthine defective patients[3] rarely suffer from cybersickness or visually induced motion sickness [27], [28], [29].

[3] That is, patients with bilateral vestibular hypofunction.

Even when sitting still, normally functioning organs of balance are sensitive to the orientation and magnitude of gravity, and sensing no motion is fundamentally different from not sensing motion. Because labyrinthine defective patients do not have a vestibular sense of orientation this explains why they do not suffer from VIMS.

The most cited theory of motion sickness is the sensory rearrangement or conflict theory as outlined by Reason and Brand [17]. This theory explains motion sickness not only in terms of a conflict between the individual senses, such as visual-vestibular conflicts, but, more importantly, as a conflict between the current sensory information and the sensory pattern that would be expected based on previous experience. The conflict between sensed and expected motion explains motion sickness in blind people and incorporation of previous experiences accounts for anticipation and habituation. This principle has been elaborated on mathematically with respect to mere physically-induced motion sickness [30], [31], [32], [33], [34], [35], thus allowing for quantitative predictions. As labyrinthine defective patients do not usually suffer from visually induced motion sickness, the vestibular-expectation conflict[4] can be assumed the primary cause of cybersickness and this basic conflict is merely modulated by a visual-vestibular conflict [4], [33], This implies that the presence of visual-vestibular conflict should not be considered a sufficient cause of motion sickness *per se*. This, likewise, explains why vision can both decrease or increase sickness. When looking at the horizon from a car or ship, matching visual and vestibular cues decrease the vestibular-expectation conflict and thus reduce the severity of motion sickness. When looking inside a vehicle (e.g., at a book or smartphone), differing visual and vestibular cues increase the vestibular-expectation conflict, and thus increase motion sickness severity. Although rather successful, the conflict theory has not yet answered all questions, such as about individual susceptibility and the measurability of neural store.

An alternative to sensory rearrangement has been forwarded by Ricco and Stoffregren [19], [36], stating that postural instability is a necessary and a sufficient condition preceding motion sickness. The latter theory, however, has been doubted, because it does not reckon for the fact that labyrinthine defective patients most often do not suffer from motion sickness, while they do show more postural instability. Nor does it reckon that Ménière[5] patients do suffer from nausea and vertigo as if they are motion sick, even when lying immobile in bed. An equal argument holds for paraplegic patients who do suffer from motion sickness. Also, it does not unambiguously predict how postural instability and motion sickness are (cor)related (by which measures, positively or negatively?), while both positive and negative correlations on sway measures have been observed [18], [21], [37], [38], [39]. One study, furthermore, found that the individual's natural sway frequency causes sickness rather than postural instability being a signature of preponderance to sickness [40].

While modulating posture and sickness, several studies furthermore showed results in favor of the sensory conflict, rather than the postural instability theory, as reviewed in Ref. [18]. One particular observation reviewed concerns the decrease of sickness often found over repeated simulator exposures, typically accompanied by an increase of postural sway [41]. The claim that postural instability precedes sickness can furthermore be doubted when considering the almost immediate effect of certain (cross-coupled) Coriolis maneuvers on sickness, an effect also reported anecdotally by astronauts of the International Space Station (ISS). The ISS consists of compartments, whereof the inventory is typically oriented in one single direction, and which are connected by tubes without such visual cues. Immediate sickness has been reported after floating from one compartment to another while being unaware of a coincidental body yaw rotation during their transit to the next compartment that then appears in an unexpected orientation. Also, in this case the role of postural stability is doubtful.

[4] That is, the failure of the VR stimulus to provide expected vestibular stimuli consistent with the ambient visual cues.

[5] Ménière's disease is a condition of the inner ear, which typically causes attacks of dizziness with a spinning sensation (vertigo), hearing loss and noises in the ear (tinnitus).

Other popular theories include the poisoning theory, which focusses on the observation that animals that vomit due to certain toxins do not do so anymore in case of ablation of the organs of balance [16]. Treisman's evolutionary theory [11] is based on this same observation. Eye movements have also been attributed a causal relationship [42], [43], which may seem to oppose the observation that blind people suffer from motion sickness [23], but can be thought of as auxiliary when considering that eye movements are involved in vision, hence contributing to cybersickness as a modulating factor. The velocity storage theory [44], [45] focuses on the observation that the time constant of the decay of nystagmus after a sudden change of angular head velocity is considerably larger than would be expected based on canal dynamics, in particular in the horizontal plane. This mechanism has generally been accepted to be controlled by the central nervous system, which mechanism also holds for perception. Moreover, velocity storage has been shown to be at issue in explaining differences in susceptibility to motion sickness, including differences due to habituation [32], [44], [46], [47], [48], [49].

Another category of theories focuses on the role of abdominal factors, such as the biomechanical hypotheses by Golding and Gresty [50] and Von Gierke and Parker [51]. Bilateral otolith asymmetries have also been assumed causal [52], [53], [54], [55] and a psychological basis of arousal is suggested by Bruck and Watters [56]. Combining several ideas, Bowins [57] posited that motion sickness evolved as a potent negative reinforcement system designed to terminate motion involving sensory conflict or postural instability. In Lawson [10] the reasoning leading to this (syn)thesis is, however, denied. Although framed and named differently, the twist and stretch theory by Holly [58] basically aligns with the conflict theory by Reason and Brand [17]. Although visual rest frames (typically Earth fixed) have been mentioned as a crucial factor in cybersickness [59], [60], [61], it remains open for discussion whether this can be considered a distinctive theory or the consequence of the conflict theory, in particular as formulated by Bos and Bles [31]. Motion sickness lastly has also been assumed to be an evolutionary remainder of our ancestors, the fish. In fish, the swimming bladder, located near the stomach, is regulated by the organs of balance, its neural innervation still having an effect on our stomachs nowadays [14].

2.5 OPERATIONAL NEEDS

The recent advances in display technologies undoubtedly offer many possibilities specifically for military land, sea, air, and space applications.

From a military procurement point of view, there is a need for robust and prioritized recommendations and guidelines that will help to ensure that system specifications and requirements take into account the technical factors (and other factors) that have been shown to be most associated with cybersickness. Ideally, technical factors will be accompanied with concrete values or thresholds (e.g., required refresh rate, etc.) previously shown to minimize cybersickness in VR systems. These values could then be communicated in updates to military standards. For example, in aviation, various certification specification documents already exist and include requirements for more traditional display technologies (e.g., full domes). Such information can produce a cost-savings to the militaries of the world by avoiding procurement of systems without the necessary specifications to be usable.

From the military end-user point of view, there is a need for an up to date 'one-stop' document that provides information on the following main areas in relation to cybersickness: symptoms, causes, effects, measurement/monitoring, and amelioration methods. For example, furnishing military training managers with information on recommended usage duration, symptom monitoring techniques and amelioration methods could reduce the potential for military personnel to experience cybersickness, stop using the technology, negatively impact other work tasks, or change their behavior when using the technology (leading to reduction in training transfer).

Lastly, there are several reasons why cybersickness is of interest with respect to the military in particular, e.g., apart from recreational or other VR settings. First, there are military training scenarios anticipating certain possible future conditions for which no real analogues exist yet, wherein training using VR could be beneficial. Second, VR allows for training scenarios that carry a high safety risk and may even be unethical to be trained for in real life, such as an airplane engine failure at low altitude. When having to deal with the upper ends of the spectrum of force, this is of particular relevance. Moreover, different from gaming applications optimized for the fun-factor, military applications are optimized for performance. Military applications should therefore provide the user with an as high as possible realism, to reduce the chance of inappropriate performance or even a negative transfer of training, while a high visual fidelity may increase the chance on cybersickness (see Section 2.3). Note that this argument not only considers visual fidelity, but also regards auditory, haptic and many other cues. Lastly, but pointing to a fundamental difference, a user gaming for fun is free to withdraw from the exposure whenever he or she likes, without further (professional) consequences. When, however, as in military training, the use of VR is part of a regular doctrine, the user will not always be free to withdraw without further consequences for her or his career. Moreover, the latter poses additional questions when considering that cybersickness is a normal response of perfectly healthy people, merely due to the use of VR. It is therefore of specific military interest to reduce cybersickness to the lowest possible minimum.

2.6 REFERENCES

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Chapter 3 – DEFINITIONS

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3.0 INTRODUCTION

In the following section, definitions and descriptions of important topics are provided and background information is elaborated on. This should allow for the use of a common terminology and inhibit misunderstanding and confusion of concepts. It is the goal to keep these as concise and clear as possible. However, if necessary, opposing viewpoints are explained and disentangled.

3.1 VIRTUAL ENVIRONMENT

Definitions of virtual environment, virtual world, virtual reality, and comparable terms are not universally agreed upon in the literature; even though there is substantial overlap, clear-cut distinctions are often missing. A definition of *Synthetic Environment* put forward by the NATO Modelling and Simulation Group 120 was as follows: *A synthesized representation of the real world* [1]. While easy and straightforward, it does not describe in sufficient depth a couple of points relevant to this work. Since a lengthy discussion of pros and cons of fine-grained definitions is out of scope for this report, one formulated by Schroeder in 1996 [2], also relating to the technological aspect, serves as a more elaborate starting point "[Virtual environment technology as] a computer-generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in, and to interact with that environment" ([3] p. 25). Core concepts of a virtual environment become clear here: a sense of presence through a technical medium (Schroeder in this definition only mentions computer-generated displays; other modalities might as well be incorporated) in a different perceived environment and the possibility to act within it. Even though this definition was already postulated in the 90s, it still mostly holds true today in covering the core concept. Since then, massive improvements were achieved in the technology related to virtual environments, especially the visual mediums through which the environment is presented have made significant steps towards higher degrees of immersion and flexibility in use [4]. In the field of visual presentation HMDs are of special importance. The uplift in the development of related technology has been described as the second wave of VR and encompasses devices like haptic vests, motion platforms or hand-tracking, further making the way for more immersive and theoretically more effective, but also sickness inducing, use of simulators.

3.1.1 Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)

Technological vernacular changes constantly as various terms are ascribed to emerging and new technologies. When one uses the term reality, it invokes connotations of the real world and the state of things rather as opposed to ideas or fantasies. Many new "realities" exist as new idioms are coined. To frame the discussion, definitions will be provided, and distinctions made for augmented reality, virtual reality, mixed reality, and extended reality, as better depicted in Figure 3-1. Distinction between the terms is subjective and delineations unclear. Definitions and common use cases presented here are not intended to be comprehensive nor authoritative and are open to interpretation.

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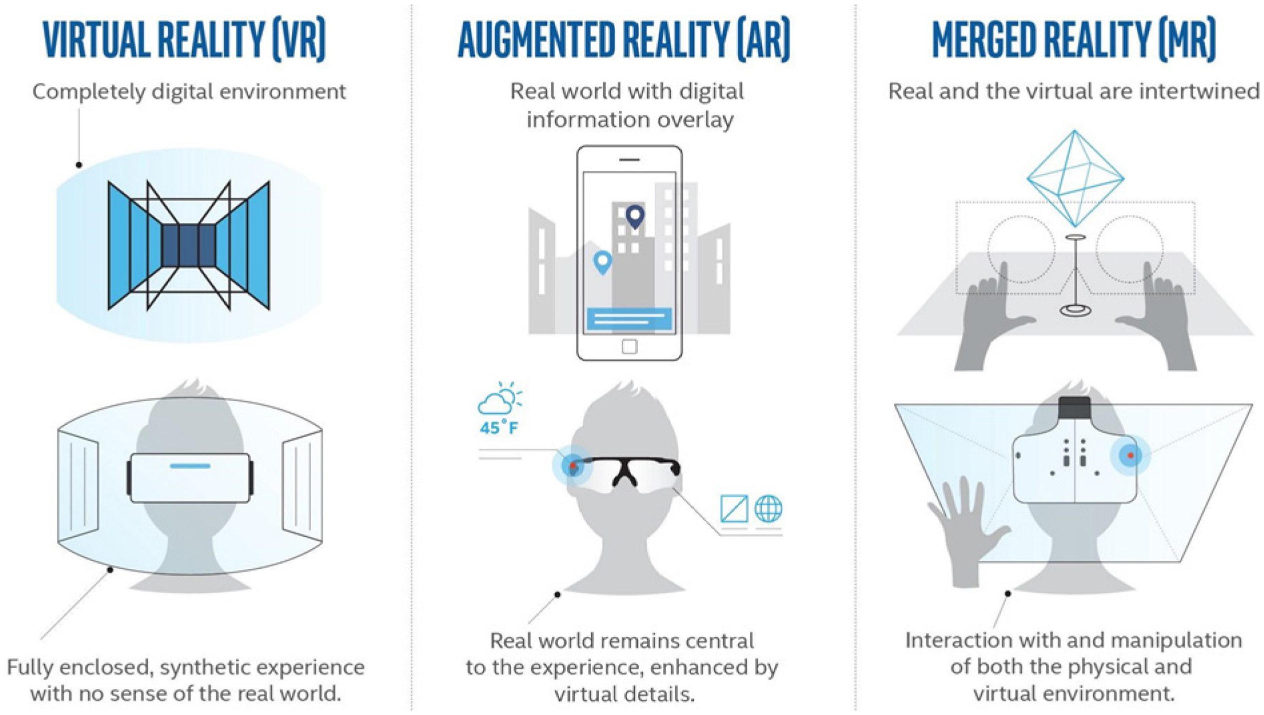

Figure 3-1: Differences Among VR, AR, and MR [5].

Augmented reality is defined by various sources as presented in Table 3-1.

Table 3-1: Definitions of Augmented Reality.

Source	Definition
Dictionary.com	An enhanced image or environment as viewed on a screen or other display, produced by overlaying computer-generated images, sounds, or other data on a real-world environment [6].
Modelling and Simulation Coordination Office AND NATO Modelling and Simulation Related Terms (MSG-120)	A type of virtual reality in which synthetic stimuli are registered with and superimposed on real world objects; often used to make information otherwise imperceptible to human senses perceptible [7], [8].

Thus, a simple working definition of augmented reality is a digitally enhanced view of the real world.

The U.S. Army, in 2019, inked a $480 million contract to purchase a specially modified version of the Microsoft HoloLens 2® headset termed the Integrated Visual Augmentation System (IVAS) [9]. The Army plans to use the headset not only to supplement training, but they also plan to use it operationally in the future, e.g., to aid identification of friends versus foes [10]. Beyond the IVAS, well-known augmented reality hardware runs the gamut from ubiquitous smartphones to sophisticated environment-sensing displays such as the Microsoft HoloLens® and Magic Leap One®.

In contrast to augmented reality, virtual reality generally denotes a fully contained virtual environment. A typical setup for presenting virtual reality occludes the wearer's view of the world. Traditionally, real-world elements are not used in a virtual reality context; rather, the setting for the user is completely virtual and contained within the simulation and headset. Virtual reality generally adheres to the following characteristics:

- Stereoscopic visual presentation.
- Fully occludes the view of the wearer.
- A (head-) tracking system to determine the wearer's location and/or orientation.

In 2003, the NATO Research Study Group 28 (RSG 28), then Human Factors and Medicine, HFM-21, defines Virtual Reality as:

> *Virtual Reality is the experience of being in a synthetic environment and the perceiving and interacting through sensors and effectors, actively and passively, with it and the objects in it, as if they were real. Virtual Reality technology allows the user to perceive and experience sensory contact and interact dynamically with such contact in any or all modalities* [11].

Common examples of virtual reality hardware include mainstream headsets like the HTC Vive®, Oculus Rift®, and Playstation VR®, but also include smartphone-based products such as the Google Daydream® or Samsung GearVR®. One of the more popular virtual reality games is Beat Saber®, a musical rhythm game where players use virtual "lightsabers" to slice oncoming elements to the beat of the music. Beyond games, virtual reality is being employed by militaries around the world as a means of cost-effective training especially for tasks that are highly visual spatial in nature.

Mixed reality extends upon virtual reality by using the same hardware that fully occludes the wearer's view. Virtual reality is extended into the real world using sensors that gather information from the real world and present it to the user. Using one or more outward facing cameras is a common way of extending virtual reality into the realm of mixed reality. Cameras are used to get a view of the real-world environment and that information is selectively provided to the user whilst the user is immersed in a virtual environment. A mixed reality flight simulator, for example, may surround a physical cockpit with a green screen closet. Outward facing stereoscopic affixed to the headset gather a view of the real world that correlates to the user's virtual view. Chroma keying is used to display the virtual world wherever green is viewed by the cameras while the remaining areas maintain a live view as provided by the outward facing cameras. In such an example, mixed reality can perhaps address a pressing shortcoming of virtual reality technology in that the user often has great difficulty accomplishing natural, real-world interactions.

In 2011, the DoD M&S Glossary [7], defined augmented/mixed reality as follows:

> *A field of computer research which deals with the combination of real-world and computer-generated data. The merging of real-world and virtual reality to produce new environments where physical and digital objects can co-exist and interact in real time, to include augmented reality.*

Finally, the traditional definition of extended reality includes the definitions provided above for augmented reality, virtual reality, and mixed reality and the continuum between them.

3.1.2 Visual Technology

The convincing and immersive creation of virtual environments depends heavily on the visual aspect of the presentation. Consequently, the interface through which these are presented plays a major role and is reflected in the focus of research and technology development in that area (see above). Different means have been and are employed for this purpose; the most widely used ones are Virtual Dome, Cave Automated

Virtual Environment (CAVE) and Head-Mounted Displays (HMDs). All of which ideally produce a stereoscopic image and aim for comparatively high immersion to create an interactive and engaging environment for the user [12], [13]. Although stereoscopic images seem to be preferred, monoscopic presentations are also possible with the aforementioned technologies and might be used due to technical or time constraints.

3.1.2.1 Virtual Reality Goggles

Another display technology that is extensively used to present users with virtual environments are Virtual Reality goggles, a form of HMD). These devices are strapped onto the head of the user and make use of an integrated screen to display visuals, while occluding any other external imagery. Usually, each eye is presented with a slightly different image to allow for stereoscopic perception. Furthermore, VR goggles usually employ head tracking to directly translate head-movements into the corresponding shift in the picture. This is achieved through different features like gyroscopes, accelerometers, or structured lighthouse systems. There are multiple manufacturers for the devices with varying specifications regarding field of view, screen resolution, refresh rates, etc. In addition, some already have features implemented like eye-tracking or outward facing cameras. Generally speaking, VR goggles have been found to illicit more cybersickness than desktop screens or theatre settings [14]. A comprehensive overview is given by Anthes et al. [4]. An example of commercial grade VR goggles is shown in Figure 3-2 [15].

Figure 3-2: Promotional Picture of Commercial VR Goggles [15].

3.1.2.2 Dome

Domes use a spherical or hemi-spherical screen on which the image is then projected to generate a wide field of view; it is comparable to the technique used in a planetarium [16]. The user in the middle of the dome is then usually wearing shutter glasses (or similar) to perceive the stereoscopic images as intended. Domes also possibly feature body and head-motion capturing systems, allowing to accommodate the user's movement within the given spatial limits of the device [17]. Domes can also feature interactive elements employed through means like handheld controllers. It has been argued that the spherical shape of the surrounding makes for a more naturalistic and immersive user experience [18]. An example of a dome is provided in Figure 3-3 [17].

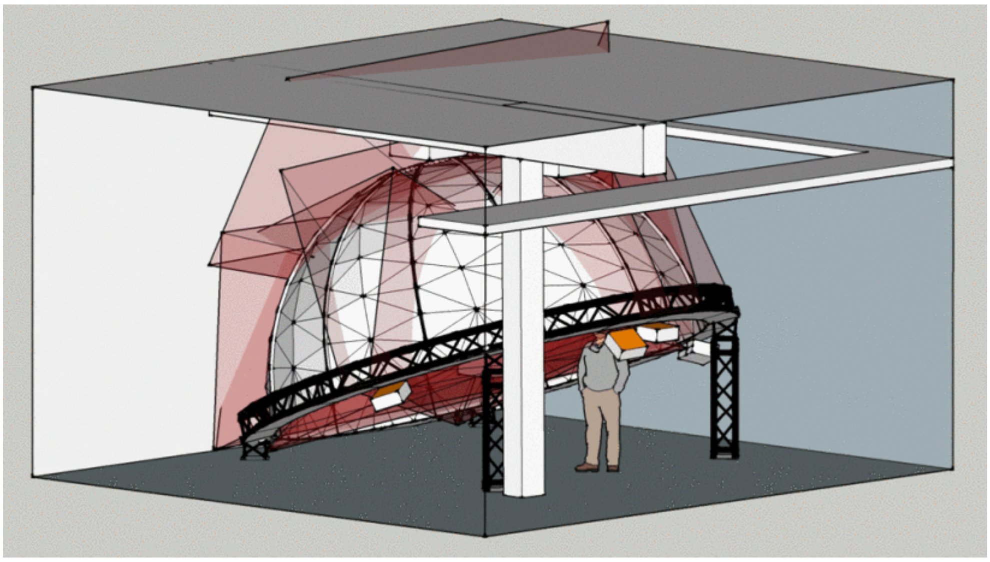

Figure 3-3: Example of a Spherical Dome Projection System from Grogorick et al. [17].

3.1.2.3 CAVE

Cave Automatic Virtual Environments (CAVEs) are very similar to domes regarding the underlying concept; stereoscopic images are projected on screens surrounding the user. The main distinction is the arrangement of the screens, which are flat and usually arranged in a cubic shape, thus not providing a spherical view [19]. An example of a CAVE is shown in Figure 3-4 [20].

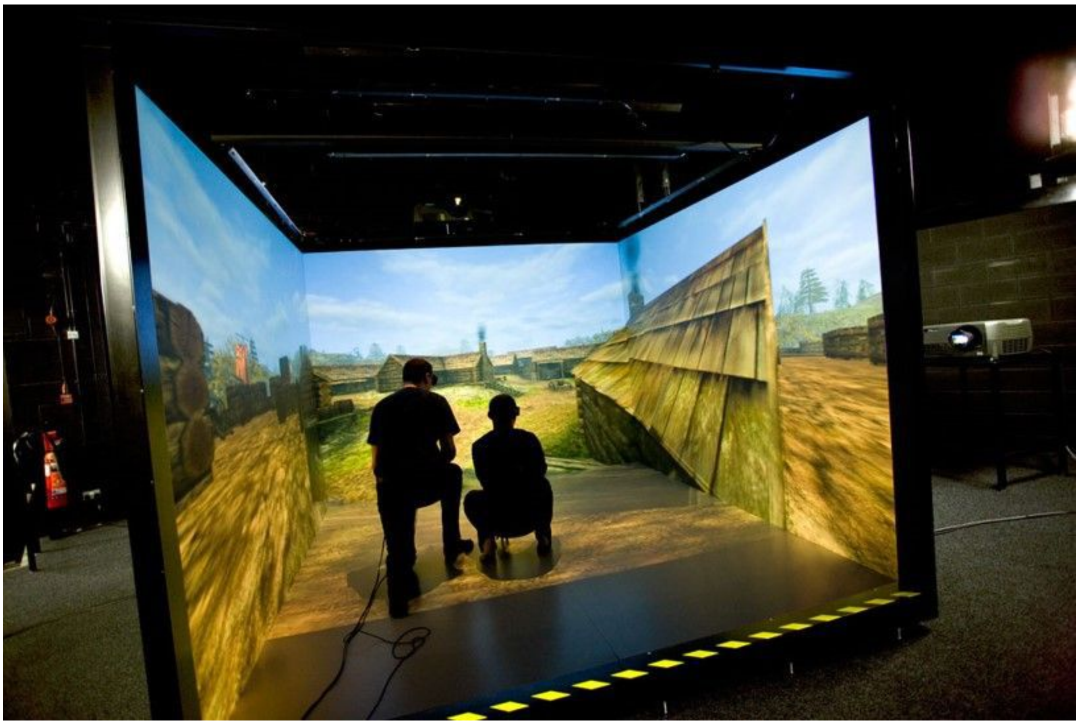

Figure 3-4: Example of a CAVE Setup [20].

3.1.3 Immersion and Presence

The Modelling and Simulation Task Group 120 have described the concept of immersion as follows: *Immersion into a simulation system is a perception of being physically present in a non-physical world*. However, in the scientific literature the definition is a little more nuanced and makes a distinction between immersion and presence. Immersion is described as the degree of sophistication of the technology used to present a virtual environment. It is a core topic regarding simulation and strongly associated with simulation fidelity. Slater and Wilbur [21] describe it as a 'quantifiable description of technology' mostly influenced by the following four dimensions of the visual display: inclusion, extensiveness, surrounding and vividness. Expanding on the aforementioned criteria, the comprehensiveness and quality of other factors also effect immersion; these include audio presentations, physical properties of the simulator, incorporation of motion, etc. Closely related to immersion is the concept of presence, which is the state of mind an individual has that can be described as 'a sense of being there'. High immersion contributes to a higher degree of presence, which makes for more naturalistic interaction in the simulation and has been associated with higher effectiveness of training.

3.1.4 Motion Platforms

To add physical motion to the simulation, and increase the degree of immersion, motion platforms are used. These provide, within their physical and computational limits, motion that is as closely resembling as possible to that in the virtual environment. Motion platforms come in various shapes with differing levels of sophistication; most prominent parameters that may vary are the degrees of freedom (up to six: surge, sway, heave, roll, pitch, yaw), the motion range, maximum possible accelerations, and decelerations (which are directly related with the motion range) or maximum payload. Another important factor are the used motion cueing algorithms, or wash-out filters, that are translating desired (e.g., motion in the virtual environment) into real motion of the platform. Due to the inherent limitations of physical space and maximum use of available motion range, each motion platform does reach a threshold when simulating prolonged accelerations. Motion platforms of three different grades are presented in Figure 3-5 [22], [23], [24].

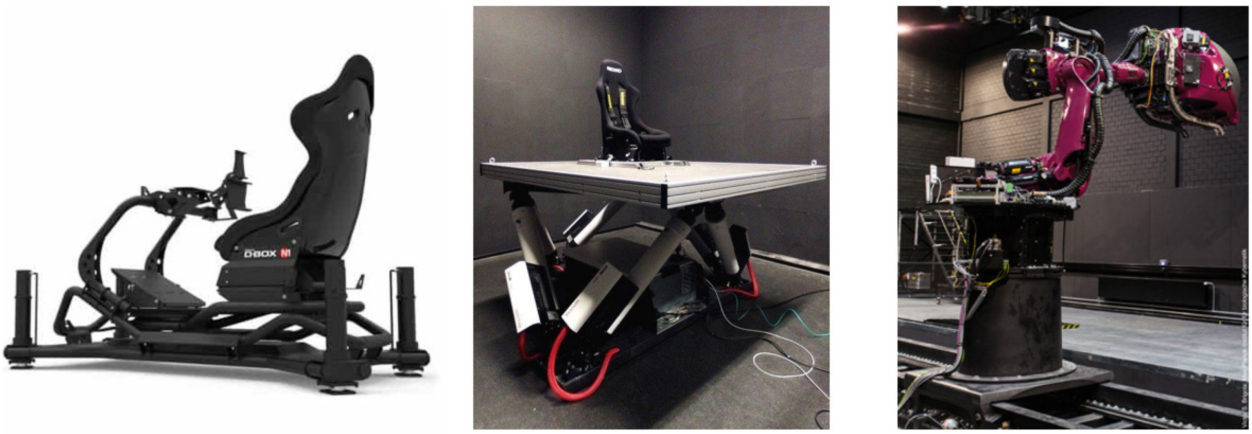

Figure 3-5: Different Motion Platforms with Increasing Degree of Sophistication (Refs. [22], [23], [24], respectively.)

3.1.5 Haptic Presentation

There are also multiple haptic devices that aim to enrich the presentation of the virtual environment in simulation settings. Dangxiao et al. [25] analyzed the development of haptic devices in the last 30 years and argue that currently the technology is following a paradigm they call ‘wearable haptics’ which includes devices that are worn by the user. According to them the focus lies on hand-worn devices and gloves that provide force feedback, allow for manual interaction and manipulation in a virtual environment and provide sufficient degrees of freedom to accommodate the motion of the single fingers. Examples of such devices are displayed in Figure 3-6 [25].

Figure 3-6: Examples of Haptic Feedback Gloves [25].

Even though haptic feedback for manual operations seems to be main area of interest, there are other devices for providing tactile information like vests with multiple vibration motors [26], [27], [28], wrist-worn devices or vibrating or poking surfaces on chairs. There are also possibilities for non-contact haptic feedback through for example air vortexes or ultrasound (e.g., [29]). Furthermore, there has also been work on the manipulation of the sensation when touching surfaces through e.g., friction modulation of touch screens.

3.1.6 Auditory Presentation

On the software side, a large topic of research for auditory presentations within virtual environments is how spatial sound is modelled and constructed [30]. This concerns mostly how and where sources need to be placed in order to evoke a compelling sensation in the user as to where the noise is coming from in the virtual environment. The differences in hardware used for presenting sound within a virtual environment are comparatively small. They are usually headphones or stationary speaker systems. Distinctions lie primarily in their power, frequency range, and their sophistication in regard to producing surround sound, i.e., the number of possible physical sources (e.g., 5.0 system with 5 sources and a 10.1 with 10 sources). More sophisticated stimuli incorporate the user’s head transfer function and introduce 3D sound via simulation of natural spatial cues.

3.1.7 Single and Multi-User

It is possible to engage within a virtual environment either alone, in a team or with non-related others whose actions do not directly affect me. Especially in the context of training simulation acting as a team in the same environment is especially important, since most e.g., vehicles are operated by a crew rather than by an individual. This poses special challenges for the simulation and the virtual environment as all members have to be present in the same one and changes and manipulations need to be directly updated within this, in order to be perceivable by all actors in real time.

3.2 APPLICATION DOMAINS

In the future NATO and its members will face new and complex security challenges due to a number of factors including: a shift in global power, natural disasters (which are likely to increase due to climate change climate change) and rapid innovation in technology (e.g., artificial intelligence) that is accessible to all. This means that NATO members must continue to invest in innovation, so that the benefits of new technology can be harnessed while mitigating the risks that emergence of new technology will bring [31]. Virtual Reality (VR) is a technology area that has the potential to transform the way many defence tasks are performed in a number of application areas and domains. This section of the report sets out what the application domains and areas are and proposes what the NATO requirements for VR technology might be.

3.2.1 VR Application Areas

The NATO Modelling and Simulation Master Plan (NMSMP) [32] sets out the following application areas:

- **Support to operations** (operational planning, analysis, decision making) – this area includes activities that are conducted to ensure that NATO, member states and operational commanders have the right capabilities to enable them to decide upon, initiate, sustain and successfully conclude operations.
- **Capability development** (defence planning, concept development and experimentation) – this area includes activities that help to improve military capabilities in order to enhance interoperability and effectiveness of NATO members.
- **Mission rehearsal** – this area includes activities that relate to the preparation and rehearsal for a planned operation or course of action. This mitigates risk and improves knowledge and awareness of situations.
- **Training and education** – these activities include collective training, individual education, exercises, and training events that enable NATO organizations, member states, partner nations and non-governmental organizations to conduct their assigned tasks.
- **Procurement –** these activities included tasks that support the total lifecycle of assets and systems, to ensure defence procurement delivers value for money for member states.

In addition, the NATO HFM-MSG-323 ST have decided to include **medical and rehabilitation** as an application area. Medical and rehabilitation covers a set of activities that contribute to the preparation and preservation of the human potential by full and coherent care [33].

Table 3-2 contains some examples of use cases where VR is already in use and potentially could be used within defence. These use cases are separated into the short term (currently implemented or could be implemented immediately), medium term (within 2 – 5 years), and long term (5+ years).

Table 3-2: VR Application Areas.

Application Area	Short Term (0 – 1 Years)	Medium Term (2 – 5 Years)	Long Term (5 Years +)
1) Support to Operations	Collaborative planning – VR is being used by scientists to facilitate collaborative working [34].	VR command post allowing for multiple participants to conduct an operation remotely [35] or for post-mission analysis [36].	VR could be used as part of telexistance systems, allowing users to operate in remote locations without being physically present [37].
2) Capability Development	Plaform designs can be reviewed in VR before being approved.	Distributed wargaming conducted in VR.	Platforms are designed and reviewed only using virtual reality technology.
3) Mission Rehearsal	Virtual reality parachute trainers are being used to rehearse emergency parachute procedures. [38].	VR enables commander and their subordinates to visualize the battle space and practice complex missions while being co-located or distributed at different locations.	
4) Training and Education	VR is used for individual training and education events such as flying training.	VR is routinely used for team [39] and collective training (distributed and co-located) [2] [40]. It is also used to deliver organizational level training such as military annual training tests.	VR is a business-as-usual training tool across the training and education spectrum.
5) Procurement	VR is used to visualize future concepts such as future platforms.	VR is used to visualize and conduct human factors evaluations of new assets before going into the procurement process.	Assets are designed collaboratively using VR systems.
6) Medical and Rehabilitation	Some training (surgical training) and rehabilitation (Stroke rehabilitation) exercises are conducted in VR [41]. Phobia and post-traumatic stress treatments have been tried also [42].	VR is used to visualize and interact with medical images for surgical planning and training [43].	VR simulators are used to guide micro-robots that are undertaking minimally invasive surgical procedures [43].

3.2.2 Operational Domains

The NATO organization and allies operate in five discrete warfighting environments (Land, Maritime, Air, Space, and Cyber) in order to achieve objectives in support of a mission. These warfighting domains are also combined together in the joint environment. The application or operational domains are defined as discrete spheres of military activity within which operations are undertaken to achieve objectives in support of the mission [44]. It is anticipated that VR technology will have some applicability in all the domains across all the application areas listed in the previous section.

The Land domain is unique in that people live within this environment, and operations need to factor in the presence of people as well as the physical infrastructure. The operational environment can be visualized and understood through a number of aspects including political, military, social, informational, and infrastructure aspects [45].

The Maritime domain is where maritime operations occur and this can be defined as an action performed by forces on, under, or over the sea to gain or exploit control of the sea or to deny its use to the enemy [46].

The Air domain is defined as the global airspace, including domestic, international, and foreign airspace, as well as all manned and unmanned aircraft operating, and people and cargo present in that airspace, and all aviation-related infrastructure [47].

The Cyber domain is defined as an operating environment consisting of the interdependent network of infrastructures (including platforms, the Internet, telecommunications networks, computer systems, as well as embedded processors and controllers), and the data therein spanning the physical, virtual, and cognitive domains [44].

The Space domain starts at the altitude where atmospheric effects on airborne objects become negligible [48].

3.2.3 Challenges of Adopting VR

This section briefly covers some of the barrier associated with adopting VR.

3.2.3.1 Cost

Rapid advances in VR technology have significantly improved the quality of current VR HMD, as well as significantly reducing the price of each HMD. However, the cost of the HMD that is required will depend on the particular use case, for example, a standalone HMD such as the Oculus GO® will cost ~€166 ($199) [49] and this will be appropriate for basic use. For an activity such as flight simulation where higher refresh rates and higher screen resolution are required, higher cost will be incurred for the HMD (e.g. HTC VIVE pro 799® [49]), the computer required to drive it, as well as the software and other peripherals. Assuming that most individuals require their own headset due to hygiene and access reasons, the costs of procuring HMDs and supporting technology could be significant, acknowledging the fact that buying in bulk may come with economies of scale and scope.

3.2.3.2 Security and Privacy

Being able to operate securely is a priority for NATO members, due to threats from hostile nations and non-state actors, so all equipment should meet the accreditation standards of NATO and the individual nations using the equipment. As of 2020 high-end virtual reality systems have had the ability to track body movement at approximately 90 times per second allowing the scene to be displayed correctly, meaning that the lag between a user moving a body part in VR and the visual scene update is now very low [50]. This information is crucial for the uses such as understanding if the user has performed the correct movement, but this information could also be used to infer what the task being completed is, risking the exposure of sensitive procedures. The information could be used to infer the physical/mental state of the user (i.e., injury or illness). This information is sensitive to the organization and the user so it must be protected and used correctly. The issue of security and privacy becomes more acute with VR in operational environments, especially the cyber domain (e.g., to visualize networks).

3.2.3.3 Requirements

The NATO Science and Technology Trends Report [51] states that NATO and its members face an ever changing, unpredictable and dangerous security landscape. Therefore, there is a requirement for investment in technology to enhance the capability of NATO members to ensure that they maintain continued success in the operatiosaklnal environment.

Operating in this environment will require multiple nations to work together using complex systems. This will require more detailed training of the ability to operate with agility in order to respond to rapidly changing threats. Live training is becoming increasingly rare due to the high demand on resources, potential inherent danger, and distance between participants.

Modelling and Simulation (M&S) has traditionally enabled NATO to support individual team and collective training events, however there is a requirement for M&S to support the other application areas set out in the NMSMP [32]. To enable the tools to be effectively used across NATO, they must be cost-effective, have appropriate standards in place, and provide a benefit. Low-cost VR technology has a role to play in support of the tasks set out in the NMSMP, as it allows users to interact with and visualize simulated environments, potentially transforming how NATO activities are conducted in the future. For example, there are potential cost saving as VR may allow users to interact in a naturalistic way, reducing the need for travel or VR could be used as novel human machine interface tool, which could improve the operational effectiveness of the user

The NATO Science and Technology Trends Report has identified VR as being an enabling technology to help users visualize and understand complex information and human augmentation technology to enhance the capability of NATO personnel. Additionally, VR will be a key part of autonomous systems, helping to improve system operation and situational awareness by providing an intuitive operation system and situational awarenessm by presenting information in a way that supports the visualization of multiple sensor feeds [51].

In the short to medium term there are likely to be increasing requirements for VR technology to support training and education. This is partly in response to the growing body of evidence that suggests VR is an effective training medium for training and education. For example, VR is widely used in firearms training to teach marksmanship [52] and decision-making skills in individuals. VR has also been shown to be an effective medium for developing maintainer skills [53], this is important as there is a shortfall in skilled engineers [54].

The requirements for VR are likely to be unique to each NATO member, but military training and education is critical enabler for NATO as it allows the different organizations to conduct training events effectively and efficiently together. There is a requirement to understand how VR can be used to support collective training events; this work is being undertaken by the United Kingdom under the Virtual Reality for Land Training project [40] and by the United States Army under the Synthetic training program [55].

3.2.4 Operational

In order to gain and maintain advantage in the operational environment there is a requirement to invest in VR technology that will support the following technologies:

- Autonomy (unmanned vehicles) – there is a requirement for unmanned systems in all domains to unite the human and the unmanned system where appropriate. VR could be a form of novel human machine interface, allowing the user to control the assets or visualize the data in a unique way.
- Human augmentation – there is a requirement to understand how VR will enhance the capabilities of human operators. The use of VR as a human augmentation tool may allow humans to be removed from theatre and operate remotely through telexistance systems. VR could also be used to allow planners to view immersive visualizations of the operational environment in 3D. This may assist with the planning process as users are able to experience the operational environment prior to deployment. Additionally, VR systems could be used as part of heads up display systems for dismounted soldiers and those operating vehicles. This is due to advances in VR technology that allow real world imagery to be mixed with virtual imagery using the cameras on the front of the headset e.g., target information.

3.2.5 Medical and Rehabilitative

NATO Centre of Excellence for Military Medicine (MILMED COE) is the organization within NATO that provides oversight to the key areas in NATO's medical transformation. One of the goals of MILMED COE is to deliver excellence in military medical (individual and collective) training [56]. Medical practitioners must maintain a high level of expertise to ensure patient safely, with errors having a high cost. Simulation is commonly used in the medical domain [57] to allow practitioners to practice medical skills effectively and safely in an environment that replicates a situation that they could face in the field. VR technology can be combined with haptic devices to develop effective training solutions and a review of the evidence suggests that VR training should and now has been included in the medical curriculum [58]. As the operational environment is becoming more complex, medics will be faced with a wider variety of medical scenarios, so the training solutions that are used must provide the capability to prepare for these. For example, remote teleoperations are of growing interest for military care in austere environments [59], [60]. Realistic simulation training is especially important when the skills are rarely used. For example, the lessons learned document from the 2017 terrorist incident in London state that VR be used to train less familiar surgical skills [61].

Combat and Non-combat injuries are common within the military due to the nature of the role. Medical services must provide rehabilitation services to military personal to ensure that they can fulfil duties or live a full life after discharge. A study by Molloy et al [62] states that musculo-skeletal injuries have significant impact on the US Army's readiness and on soldier health. This is an issue faced by all NATO members; therefore, research must be conducted to understand how VR could be used support military rehabilitation services.

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Chapter 4 – SYMPTOMS AND MEASUREMENT

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4.1 SYMPTOMS

4.1.1 Identifying Symptoms of Motion Sickness and Visually-Induced Motion Sickness

Motion sickness and visually-induced motion sickness are characterized by a variety of symptoms, some of which can only be judged by introspection, while others can be observed as signs or objectively either through behavior or through physiological responses. Table 4-1 gives an overview of different symptoms as mentioned in all the literature reviewed in this report.

Table 4-1: Symptoms and Signs Associated with Motion Sickness. (Listed in alphabetical order.)

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			+

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Symptom	Well-Established	Neuro-Physiologic	Psycho-Logic
Lack of appetite	+	?	?
Lack of motivation			+
Nausea	+	+	?
Pallor	+	+	
Postural instability / feeling unsteady		+	
Relaxation		?	?
Retching	+	+	
Salivation (usually increased; occasionally decreased)	+	+	
Stomach or epigastric awareness or discomfort	+	+	
Stuffy feeling in the head / fullness of head	+		+
Sweating (cold sweating, clamminess)	+	+	
Uneasy/general discomfort			+
Vertigo	+	+	
Vomiting	+	+	
Yawning	+	+	

“Well-established” refers to the fact that the symptom is included in the most often-used rating scales (see Section 4.2); “Neurophysiological” here implies an assumed neurophysiological and sensory-dominated phenomenon; “Psychological” here implies an assumed a psychological or cognitive dominated and hence highly subjective phenomenon.

Some symptoms associated with motion sickness have been shown to typically appear earlier than others, on average [1], [2]. Within this progression, there seems to be a variety of symptoms that may differ between people, such as dizziness, pallor, feelings of warmth, headache, stomach awareness, difficulty concentrating, and increased salivation, but which, as a group tend to precede nausea, retching, and vomiting. This implies three major categories: pre-nausea, nausea, and retching/vomiting, albeit in situations of chronic exposure to challenging stimuli, retching, or vomiting can occur without nausea [3].

Symptoms other than those predictive of vomiting can be elicited by moving visual surrounds such as optokinetic stimuli, flight simulators, and VR, and include headache, eyestrain, and dizziness [4]. Cybersickness symptoms can be distinguished from other types of sickness [5] by their more prominent disorienting effects (such as dizziness and vertigo) as detailed further in Section 4.2. Given the adverse implications of loss of self-orientation in a military setting, such symptoms merit special attention.

In both Table 4-1, and the rest of this section, a distinction is made between (neuro)physiological and psychological effects. It should be noted, however, that there is a vague overlap between the mechanisms underlying these two descriptors, as may be exemplified by Pavlov’s reflex. What starts with a mere psychological condition may end with a neurophysiological reflex.

4.1.2 Physiological

As listed in Table 4-1, several symptoms are largely (neuro)physiological reflexes. Here, the pre-vomiting symptoms are generally associated with sympathetic nervous system activation and parasympathetic inhibition, while the opposite holds for vomiting [6]. So far, it is concluded that these symptoms can better be assessed by introspection, than by objective observations and measurements [4]. Section 4.2 will further elaborate on the rating of physiological aspects both with respect to self-ratings and objective correlates of motion sickness.

Part of the differentiation between physically and visually-induced motion sickness as referred to above, can be understood as follows. As characterized by the simulator sickness questionnaire (Section 4.2), part of the symptoms listed in Table 4-1 may cluster on Oculomotor, Disorientation and Nausea categories. In certain situations, such as head-mounted virtual reality displays, it makes sense to assume that some symptoms are dominated by accommodation-convergence conflicts, and others by visual-vestibular conflicts. Accommodation-convergence conflicts arise due to the fact that in VR with stereo images, the eyes are converging and diverging when focusing on nearby and distant objects, respectively, while the imagery is projected on a fixed distance thus requiring the accommodation of the lenses in the eyes to remain fixed. In addition, if the VR is not exactly fitted to the interpupillary distance of the user, problems can arise [7].

Such factors have been assumed a major cause of discomfort in using stereo images [8], [9], [10], [11]. Because in real life the two systems are linked, a link acquired (learnt) by our Central Nervous System (CNS) in the first six years of life, in VR this learnt link has to be unlearnt, typically Causing Eye Strain blurred vision, and headaches. Because our CNS does use afferent signals derived from eye and lens movements to estimate the depth of objects in space (their distance to the observer), this conflict may also cause dizziness (vertigo), disorientation, nausea, and postural instability. Besides a neural link between convergent eye movements and lens accommodation, pupil movements are also included, resulting in the near triad: the simultaneous converging of the eyes, the thickening of the lenses and a constriction of the pupils [12]. Though rarely studied, this may also explain non-specific pupil movements caused by VR in particular. Although these considerations may explain the overlap in symptomatology caused by accommodation-convergence conflicts on the one hand and visual-vestibular conflicts on the other, some literature suggests that, as can be expected, some symptoms can be caused by imageries that do not suggest self-motion, in particular still-images, while others are merely caused by imageries that do suggest self-motion [13]. It therefore remains an open-ended question whether cybersickness should be considered a pure form of motion sickness or not (see also Chapter 2). With respect to cybersickness, in which a vision is decidedly involved, the visual-vestibular conflict is yet of most importance (see also Section 2.3), while the visual and ocular factors mentioned here only contribute to the extent of that conflict.

A particular point of interest concerns the role of eye movements [14], [15]. Whether or not eye movements should be considered a mere physiological reflexive response, it does make sense to also assume that the other way round, eye movements can have an effect on spatial orientation and self-motion perception and hence on motion sickness in general and cybersickness in particular. Yet, as already mentioned in Chapter 2, the fact that blind people do suffer from motion sickness points to a modulating, rather than a causal relationship.

4.1.3 Psychological

The psychological aspects of motion sickness can be considered part of a general concept of subjective well-being [16]. Subjective well-being is a self-reported measure of well-being, typically obtained by questionnaires. Subjective well-being includes both emotional reactions (e.g., moods) and cognitive judgments, both in a positive (e.g., happiness) and a negative (e.g., illness) sense. Subjective well-being tends to be stable over time and is strongly related to personality traits11. The relationship between traits and motion sickness, however, remains questionable (e.g., Ref. [17]). The psychological aspects of motion sickness can be considered part of the general concept of subjective illness [18], meaning the comprehensive psychological explanations about causes and functions of actual problems. These too can be assessed by questionnaires, which are further discussed in Section 4.2.

One example of a psychological (or cognitive) factor concerns anticipation, i.e., the recognition of certain information well in advance of a provocative event. When in a car looking forward, for example, generally less sickness is observed as compared to looking backward, and inherently predictable motion has been shown to be less provocative as compared to motion with equal dynamic characteristics, except for its predictability [19], which also holds for inherently unpredictable motion made predictable by anticipatory audio cues [20]. Note that it makes sense to differentiate long-term, typically cognitive effects explaining the difference between facing forward and backward as a passenger, versus short-term effects that can be accounted for by efferent copies and re-afferent signals [21]. To emphasize the difference, this has also been termed *anti*cipation versus *per*cipation [22].

Conditioning is another central aspect of motion sickness. Having been sick in combination with a certain environment or specific odor (e.g., that of diesel fuel aboard a vessel) may cause that other condition to trigger sickness thereafter, even in the absence of motion. An analogy concerns animals not capable of vomiting, such as rodents, in which an appetite for non-foods (pica) is taken as a measure of motion sickness [23]. A similar effect also holds when exposing subjects to experimental sickening and repeated conditions. Then the anticipation to vomit again may prevent them from completing the series of exposures (see also Section 4.2.3.1 on rating motion sickness).

Mental distraction, e.g., by performing a cognitive task during motion exposure, can lower motion sickness [24], [25], [26], [27], [28], [29]. Listening to pleasant music has also been shown to decrease sickness [30], [31]. Whether the same holds for pleasant odors (both regarding its possible positive effect on sickness per se and possible explanation by means of an odor-induced change of mental state) has not been settled [32], [33].

Cognition does, lastly, play a major role in certain treatments of motion sickness, in particular those focusing on behavior and the use of biofeedback by means of physiological responses [34], [35], [36], [37]. Although a positive effect of these treatments is generally accepted, some of the physiological measures which have been used are primarily considered indicators of arousal/anxiety, so the effect may be indirect in some studies.

4.1.4 Sopite Syndrome

Given the observation that a symptom complex centering around "drowsiness" is a major part of the pre-nausea symptomatology, Grabiel and Knepton [38] suggested to term this category as the sopite syndrome. The symptom complex includes such symptoms as relaxation, drowsiness, fatigue, yawning, difficulty concentrating (e.g., fuzzy/foggy headed), apathy, and lack of motivation) and was found to appear during and after the stimulus [39], [40], [41], which sometimes can be the sole manifestations of motion sickness. Note that several of these symptoms are included in, e.g., the Simulator Sickness Questionnaire (SSQ) (see Section 4.2), implying that sopite may partially be considered the grouping of a number of symptoms, rather than being a separate syndrome. Yet, the sopite syndrome has since been studied in naval crew [42], parabolic flight [43], in tall buildings [44], using visual stimuli [45], and in many other situations [4]. Even though the sopite syndrome seems to have less severe and overt symptoms than nausea and vomiting, its effects could be insidious, and an effect on task performance has nevertheless been observed [46]. Of practical concern is the observation that yawning serves as an indicator of the onset of the sopite syndrome [47].

Addressing the overlap of soporific symptoms, the health state of the individuals, and the existence of a motion stimulus not mentioned in the original definition of the sopite syndrome [39], Matsangas and

McCayley [48] proposed a refined definition, stating that the "sopite syndrome is a symptom complex that develops as a result of exposure to real or apparent motion and is characterized by excessive drowsiness, lassitude, lethargy, mild depression, and reduced ability to focus on an assigned task. Similarly, formal attempts have been made to explore the symptom descriptors and statistically analyze the factors of sopite syndrome, which have identified a set of internally consistent symptom clusters sufficiently distinct from regular motion sickness [41]. Sopite syndrome is most clearly distinguished in a healthy individual free from pathological conditions that engender similar symptoms and not suffering from sleep deprivation, mental or physical fatigue, or increased levels of physical activity". Possible consequences with respect to rating of the sopite syndrome are discussed further in Section 4.2.

4.2 MEASUREMENT

4.2.1 Generalities

The measurement of motion sickness concerns the quantification of certain sickness characteristics, i.e., giving a number to sickness severity. Currently, the most reliable and valid measures of motion sickness entail (subjective) self-ratings that do require some form of introspection concerning feelings of illness [4]. Self-ratings measures are inexpensive and easy to administer and form the basis for the user's decision to alter their behavior or quit a VR. The counterpart of self-ratings concerns (objective) measures that can be taken by human observers (such as pallor), or by apparatus, possibly without being reckoned by the subject himself (such as changes in skin conductance).

Motion sickness questionnaires can be separated into susceptibility history (trait) questionnaires and current sickness (state) questionnaires. (Trait) history or susceptibility questionnaires refer to sickness experienced in the past that may be predictive for current or future events and are typically taken before an exposure as subject of specific investigation. State questionnaires refer to sickness at a specific moment in time, typically taken during or right after such an exposure. They permit the use of less nauseating experimental stimuli and provide finer-grain analysis of motion sickness severity levels than would be available with a binary measure (e.g., vomited or not; felt sick or not). They are typically used to determine how severe sickness got, when the peak occurred, and whether the severity or peak differed among conditions. State questionnaires yield temporal ratings of MS severity (e.g., once per minute during stimulation). The subjective state questionnaires can then subsequently be divided into a category referring to mere feelings of illness without making reference to specific symptoms, and a category that does focus on the symptomatology, in particular the progression thereof. Figure 4-1 shows these different categories, as will subsequently be discussed, and further sorted out in the next sections.

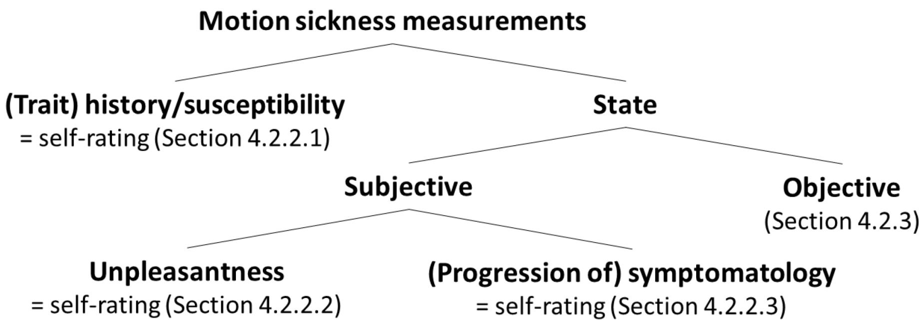

Figure 4-1: Types of Motion Sickness Ratings/Questionnaires.

Note that here "subjective" and "objective" refers to the perspective of the observer, more than it does to a possible bias confounding the measurement.

4.2.2 Self-Ratings

4.2.2.1 (Trait) History/Susceptibility

One of the most obvious observations in motion sickness studies concerns the large individual variability in sickness severity between individuals given the use of equally provocative stimuli. Besides individual factors such as age, there seem to be other physiological and psychological factors causing this variability. To get insight into this variability, as well as to obtain a prediction of susceptibility before a motion challenge occurs, motion sickness susceptibility questionnaires have been designed based on past events. Although early attempts focused on specific provocations [28], it is now believed that susceptibility to one type of sickness does not predict more than approximately 40% of the variance in susceptibility to another type [49], while there yet seems to be an overall susceptibility that tells at least something about an individual's susceptibility in general.

The two most commonly employed histories are the Pensacola Motion History (MHQ, reviewed in Ref. [41]), and the more recent Motion Sickness Susceptibility Questionnaire (MSSQ) [50], [51]. Both have good test properties and include military participants during development. The vernacular is American in the MHQ and British in the MSSQ so clarification of idioms may be necessary, but the MSSQ has been translated into several other languages, so the vernacular differences are presumed to apply only in English-speaking countries. The MSSQ, in particular the 2006 version referred to as MSSQ-short, rates sickness occurrences on a four-point scale (0 = "never", 1 = "seldom", 2 = "sometimes", 3 = "often") in nine typical kinds of motion exposure in the past 12 years, as well as in the first 12 years of life. This results in an accumulated score ranging from 0 (not susceptible at all) to 54 (extremely susceptible). Using a large dataset, Golding also estimated the MSSQ distribution for a normal population, implying a median or average MSSQ-short score of 11.3 and 12.9, respectively, for a normal (British) population [51]. The latter can be useful for screening out very low-susceptibility subjects (in studies of motion sickness), screening out highly susceptible subjects (in studies where motion sickness may occur but is not the purpose of the study), or as a covariate to aid analysis of conditional differences during a challenge.

Many studies have shown a significant correlation between MSSQ ratings and sickness severity observed in various motion situations [2], [5], [39], [51], [52], [53], [54], [55], although Bos et al. [22] found that 8/12 subjects in a VIMS study got "fairly nauseated" (p. 219) (fairly nauseated = 7 on a 0 – 10 scale) despite the group average MSSQ scoring being below the 50th percentile for all 12 subjects. Also, Lamb and Kwok [56] recommend different MSSQ norms should be used.

Recently, Keshavarz et al. [57] developed an adapted MSSQ, the Visually-Induced Motion Sickness Questionnaire (VIMSSQ), to predict susceptibility to visually-induced motion sickness, based on past experiences. Susceptibility scores for past VIMS on the questionnaire correlated well with actual VIMS during a driving simulator experiment, especially for the nausea subscale of the VIMSSQ.

4.2.2.2 Unpleasantness

These questionnaires entail subjective ratings asking about overall feelings of illness without making detailed reference to several specific symptoms. The question then generally asked for, is how bad someone feels. Limited ordinal scales have been used ranging from 0 = "alright" to 3 = "absolutely dreadful" [58], [59], or from 0 = "fine" to 10 = "awful" [1]. The latter scale, however, is not entirely free of individual symptoms, as it anchors "awful" with "like I am about to vomit". Other scales have been used as well, e.g., ranging from 0 = "no sickness at all" to 20 = "frank sickness" [30]. A review of these scales is also provided in Refs. [41], [60]. This latter rating scale, though, is not free of individual symptoms either, as it instructs subjects to more heavily weigh symptoms such as general discomfort, nausea, and stomach awareness, but to ignore fatigue, nervousness, and boredom when choosing their overall rating. Moreover, the only descriptor that appears to be have an explicit severity number assigned to it is frank sickness, which anchors the peak rating of 20.

Also, there is little evidence in the literature to suggest that 21 descriptor rating levels are needed [41]. The authors of this scale furthermore acknowledge that their scale does not assess sopite (see Section 4.1).

A claimed advantage of using these illness ratings is their speed of administration and the lack of need to explain the polysymptomatic nature of the MS syndrome (e.g., the definition of each symptom, [41]), which makes them advantageous in large-scale (typically sea) trials [58], [59].

4.2.2.3 (Progression of) Symptomatology

Among the many methods that have been tried for quantifying motion sickness, measures referencing multiple reported symptoms or observable signs are by far the most widely used. Symptom measures are inexpensive, quick to set up, field-ready, and relatively invulnerable to data loss (e.g., due to technological failure). Moreover, unpleasant symptoms are the main basis for the user's decision to alter their behavior or quit a VR and are central to interpretation of the validity of data concerning physiological correlates of motion sickness. These types of rating scales can be divided into:

1) Multisymptom, single-answer questionnaires assumed to be unidimensional; and
2) Multisymptom, multi-answer checklists (rating a list of symptoms), some of which are assumed to be unidimensional and some of which are proven to be multidimensional.

4.2.2.3.1 Single-Answer Ratings of Multiple Symptoms

Some of the earliest researchers to study motion sickness via an explicit distinction between different symptoms were Hemingway [61] and in particular Alexander and colleagues in their "Wesleyan University studies of motion sickness I – VII" [62] to [68], using sea-like conditions. Alexander et al. rated sickness on a 3-point scale: 2 = "vomiting", 1 = "unequivocal nausea and/or profuse sweating", 0 = "other, mostly no symptoms" (abbreviated definitions; [62]). As explained in Section 4.1, different categories of symptoms associated with motion sickness tend to appear before others, on average, and Alexander et al.'s rather condensed scale is just one example, in addition to examples published thereafter by Reason and Graybiel [1] and Bos et al. [2]. Within this progression, there seems to be a variety of symptoms that may differ between people, such as feelings of dizziness, pallor, warmth, headache, stomach awareness, difficulty concentrating, and/or increased salivation, but which, as a group, tend to precede the group of symptoms characterized by nausea, retching, and vomiting. For this reason, some researchers have grouped some of these earliest-appearing symptoms into categories with different severity values, the latter with the intent of refining the scale as a whole [2], [14], [39], [69], [70], [71], [72], [73]. The scale among these offering the greatest detail is the MISC of Bos et al. [2] distinguishing 0 = "no problems," 1 = "uneasiness (no typical symptoms),", from 2 – 5 = "vague to severe symptoms but no nausea", from 6 – 9 = "nausea" or "(near) retching", and 10 = "vomiting". Apart from application in studies on carsickness, seasickness, airsickness and space sickness, this scale has been used successfully in several studies on visual effects [13], [74], [75], [76], [77], [78], [79], [80], [81]. Although these rating scales based on symptomatology do require some explanation in advance of their use, when familiarized with them, subjects can easily report on their feelings of misery within a second, allowing repeated application within experimental trials, even with eyes closed.

A detail, lastly, concerns the fact that these symptomatology scales, though giving a single number, are in fact ordinal scales, which, although often analyzed parametrically, should formally be analyzed non-parametrically (but do see Ref. [82]).

4.2.2.3.2 Multisymptom Checklists

Sickness can be rated by focusing on specific symptoms and rating each individually. Each symptom is typically rated on a four-point scale (0 = "none", 1 = "slight", 2 = "moderate", 3 = "severe"). They then yield a total sickness score by summing symptoms, sometimes with additional mathematical weightings or subfactor construct scores [40]. Building on two well-established scales, the Pensacola Diagnostic Criteria (PDC) [41] and the Motion Sickness Questionnaire (MSQ) [83], 16 of the original symptoms were rescored to create the Simulator Sickness Questionnaire or SSQ [49]. Using a large military database encompassing a variety of (fixed base) simulators, factor analysis showed that the 16 symptoms could be grouped into three categories: Nausea (N), Oculomotor (O) and Disorientation (D), which scores can be integrated into a Total Score (TS) [49]. Another 12 symptoms from the MSQ are retained in the SSQ, and it has been used widely for MS.

The SSQ has been popular in VR studies and can distinguish cybersickness from other types of sickness [5] with the "Disorientation" symptom cluster being prominent (i.e., difficulty focusing, nausea, blurred vision, fullness of head, dizziness, and vertigo). Since some symptoms overlap among the clusters of the SSQ, the reader should know that the Disorientation cluster symptoms which are unique to that cluster (not shared with the Nausea or Oculomotor dimensions) are fullness of head, dizziness, and vertigo. Eight of the 16 SSQ symptoms could be of specific interest for simulator studies (viz., general discomfort, eyestrain, difficulty focusing, difficulty concentrating, fullness of head, blurred vision, vertigo, and burping), because they were retained when the MSQ was reduced resulting in the SSQ to become more specific to simulator sickness but are not featured in the PDC (which was developed mainly using real motion). The reader will notice that among these eight symptoms, three relate to eye-related problems, which tend to occur with Visually-Induced Motion Sickness (VIMS). Among these eight SSQ symptoms not featured in the PDC, five (eyestrain, difficulty focusing, fullness of head, blurred vision, and vertigo) have also been featured in the majority of the other formally-developed simulator / cybersickness scaling attempts [52], [84], [24], [17], [85], [45]. This supports the assertion that such symptoms should be of interest in simulation/VR studies (along with dizziness, for the reason mentioned above in Section 4.1. Readers will note that most of these symptoms involve either degradation of visual functioning or disorienting effects, both of which should be of concern in military operations.

Interestingly, Stanney et al. [5], made a comparison between the SSQ subscales differentiating sickness observed in simulators and several (other types of) virtual environments, concluding that simulator sickness is characterized by a high SSQ ocular, and cybersickness by a high disorientation component. It would be useful to determine whether these distinguishing symptom clusters would be seen in different simulators using different projection systems and motion bases, versus the latest models of various VR goggles.

The SSQ is the most well-known, used, and cited scale, not only among multisymptom checklists but overall. Given its military (data) basis, the SSQ is a strong consideration for NATO users. A few recent studies have questioned whether the SSQ is optimal for a civilian population using commercial VR [45]. Scales for that purpose are being developed, such as the Virtual Reality Sickness Questionnaire (VRSQ) [45], which presently, however, is still of limited value due to its embryonic phase of development. NATO countries focusing upon military personnel do not have a strong reason to shift to the VRSQ. Nevertheless, since the VRSQ is a variant of the SSQ, it could be explored during analysis of SSQ findings, e.g., in cases where commercial VR are used in a military setting and civilian comparisons are anticipated.

The Motion Sickness Assessment Questionnaire (MSAQ) [86] is a checklist developed apart from the PDC, MSQ, and SSQ, and uses slightly different symptom descriptions and a greater number of severity rating levels for each symptom. It consists of 16 items (rated 1 = *not at all* to 9 = *severely*) which are divided into four symptom clusters: Gastrointestinal (G, e.g., "sick to my stomach"), *Central* (C, e.g., "dizzy"), Peripheral (P) (e.g., "sweaty"), and Sopite-Related (SR) (e.g., "drowsy"). The wording of its descriptors was generated by laypersons instead of specialists, and many the items on the MSAQ are similar to the PDC.

It might be useful in a military VR training setting to adopt some of the phrasing of the MSAQ when explaining the training about to occur. This could ensure all users grasp the symptoms for which they should be alert and thereby ensure that any needed training pauses are not missed due to lack of understanding of the symptoms. Training could also be enhanced by ensuring that people read the definitions of the symptom criteria for motion sickness [4].

The key advantage of multisymptom checklists is that they preserve individual symptom data for fine-grained analysis of questions such as whether some stimuli produce certain symptoms more than others, whether some symptoms are reliable early warning indicators of motion sickness, whether symptoms of greatest operational concern for a particular task have emerged, or whether subjects with different individual traits have differing symptoms. Multisymptom checklists such as the PDC, MSAQ, and especially the SSQ are also reliable, widely used, and well-established, which fosters collaboration or cross-study comparison [41]. Finally, more military participants have been assessed with multisymptom checklists such as the PDC and SSQ than any other type of motion sickness state questionnaire.

The main disadvantage of multisymptom checklists is that some require up to a minute to administer, whereas most single-answer questionnaires can be administered in only a few seconds (Ref. [41], see above). If there is not sufficient time or too much interference with other tasks to administer a multisymptom checklist during a VR session, it should be administered immediately after the sickening stimulus ends, with the SSQ being the default choice for its maximal cross-study comparison and military relevance. When time is too limited for a multisymptom questionnaire during a VR session, abbreviated estimates of symptoms should still be gathered if feasible, either via a single-answer questionnaire, or by administering an abbreviated list of symptoms from a multisymptom checklist (as described in Ref. [41]). For example, the nine SSQ symptoms of the VRSQ could be assessed within 20 seconds, and then be compared to the same symptoms from the full SSQ immediately after the session is over. Of the nine VRSQ symptoms, the six with the heaviest loadings (on either of the two factors) were: eyestrain, fullness of head, fatigue, headache, dizziness (eyes closed), general discomfort. These symptoms could be assessed in about 10 seconds.

4.2.2.3.3 Apples to Apples and Oranges to Oranges

Several of the rating scales discussed above show a mutual relationship to some extent [1], which specifically holds when the SSQ is concerned [2], [30], [52]. Colwell [87] made an attempt to determine the relationship between a subjective illness rating and the Motion Sickness Incidence (MSI) based on data taken from Lawther and Griffin [58], concluding that for moderate to high MSI values, the illness rating considered relates fairly linearly to MSI, but for low MSIs it does not. From a theoretical point of view, it does not make sense to assume an overall linear relationship. First, the MSI concerns a proportion of binary observations (vomiting or not) over a certain population, whereas the other rating scales concern ordinal scales holding for individuals, possibly as a time series, and may be averaged over a certain population. Given the observation that vomiting is generally preceded by pre-vomiting symptoms that are rated by means of these scales, but not by the MSI, it can be understood that an average illness may have reached a nonzero value, while the MSI still equals zero. Taking that into account, Wertheim et al. [88] related the MSI as taken from the MISC (MISC = 10 indicating vomiting) and to the average MISC itself in twelve of their experiments [89]. They inferred a non-linear S-shaped relationship. Given the limited number of vomiting incidences included in their study, however, further research was recommended to explicate the non-linearity. Bos et al. [90], using a non-symptom related 4-point scale ranging from “no problems” to “absolutely dreadful” (taken from Ref. [58]), found that of the 49 ship passengers who did vomit, only 29 rated that as being absolutely dreadful. This supports the anecdotal evidence that vomiting may bring relief and implies that subjective feelings of illness and the progression of symptomatology concern different dimensions of the same syndrome. This assumption has recently been substantiated by Reuten et al. [91].

A specific concern relates to the fundamental difference between the accommodation-convergence and visual-vestibular conflicts. As pointed to in Section 4.1, it remains unresolved whether the visual factors discussed above in relation to the SSQ in particular, are brought about by specifically accommodation-convergence conflicts in which motion is not a crucial factor by visual-vestibular conflicts in which motion is crucial or by both. To date, there is no specific literature making this distinction while fundamental knowledge based on appropriate measurements is required to also develop the appropriate countermeasures that get to the core of cybersickness. As both factors are usually present, however, and each is sickening, the role of neither aspect should be rejected until there is evidence to do so.

4.2.3 Objective Ratings

This section will elaborate on quantitative measures of symptom severity that can either be taken by human observers or by apparatus, the latter possibly without recognition of the symptom at issue by the subject.

4.2.3.1 Motion Sickness Incidence (MSI)

The most widely used group-level index of vomiting *per se* is the Motion Sickness Incidence (MSI). The MSI quantifies the percentage of a population (e.g., passengers exposed to a given transportation situation) that has reached the limit of vomiting within a certain interval of time [92], [93]. MSI has also been called the Vomiting Incidence (VI) [69], [70]. Vomiting can be observed by the subject or by observers and can be counted easily by the number of incidences, either within one person, within a population, or, as used most often, the number of people that reached the limit of vomiting. It therefore constitutes the most obvious measure of motion sickness.

In rating the MSI, the time at which the rating is taken is an often a neglected factor. In most studies, the MSI is considered to be a cumulative rating counting the total or cumulative number of people that reached the limit of vomiting since the onset of a provocative motion. In such cases, the MSI hence cannot decrease with time. However, if defined as the number of people reaching the limit of vomiting *within a certain interval of time* as part of or after a certain motion exposure, the MSI can decrease due to habituation or recovery. In conditions with variable motion characteristics, the MSI taken over a specific interval may also increase and decrease over time. Although rarely done, it would make sense to explicitly define a cumulative MSI as well as the $\Delta MSI/\Delta t$ in which Δt should be specified explicitly.[2]

Rating numbers of vomiting people is the most obvious and decisive way of measuring sickness severity. A disadvantage, however, is that vomiting is a dichotomous event, and a large number of observations is needed (at great cost to the subjects) to resolve (mathematical) relationships. More importantly, it makes sense to consider that vomiting itself is only one symptom of the motion sickness syndrome. The MSI is therefore insufficient to provide insight in the full spectrum of symptoms (see Section 4.1) caused by certain provocations. Moreover, vomiting often can be considered the endpoint of a complex and progressing symptomatology, implying that vomiting is an incomplete measure of motion sickness "severity" as a whole. It is telling that there are many conditions in which people suffer from motion sickness, while no one vomits. The latter typically holds for conditions in which people are free to withdraw from the provocation, as in gaming and lab experiments. Closing one's eyes, limiting head movements, or taking off VR glasses are readily available remedies against cybersickness, preventing emesis in many cases.

4.2.3.2 Other (Physiological) Measurements of Motion Sickness

In the search for objective measures (sometimes also referred to as correlates) for pre-vomiting motion sickness severity, many different parameters have been considered. Typically these are based on physiological measurements and include the quantification of symptoms such as pallor (e.g., via skin blood flow; [94], sweating through, e.g., skin conductance [95], [96], [97], [98], [99], heart rate (e.g., via electrocardiography [100]), and gastric activity (e.g., via myoelectric activity [101], [102], [96], [103], [97], [104]). However, inconsistent findings have been observed for approximately a dozen different physiological correlates of motion sickness evaluated over the decades [60]. It should be noted that this is a developing area of inquiry that is not as mature as the qualitative assessment of symptoms, and no physiological measure has been found yet which captures the overall motion sickness response better than symptom reporting does. An often neglected, yet important factor concerns the observation that the studies reported on in the open literature focused on sensitivity (i.e., the chance of observing a physiological change associated with

[2] Note that considering the infinitesimal $dMSI/dt$ does not make sense, because it would reduce to zero for small time intervals and the act of vomiting itself takes time.

a certain sickening provocation), while specificity (i.e., the chance of finding no effect due to an unrelated provocation), while reports on specificity could not be found in our review of the literature. Yet to make such tests reliable and valid, both sensitivity and specificity should be high.

Irrespective of these shortcomings, the search for objective motion sickness indicators continues to be a subject of interest for more than 75 years [61], [105]. It is a common misconception, or even a technophilic article of faith, that physiological measures are inherently superior to self-ratings. Such a generalization cannot be assumed for several reasons summarized below.

- First, the search for objective physiological correlates of motion sickness is currently based on comparisons with symptomatology as observed subjectively, e.g., visually-observed pallor vs. skin reflectance, observed sweating vs. electrodermal activity, or subjective nausea vs. gastric activity [33], [106], [107]. This observation thus questions the added value of the correlations found, which have not yet replaced the "gold standard" symptom measures. Moreover, it remains doubtful to what extent objective measures will be able to temporally predict motion sickness before someone is aware of being sick. Until our knowledge of motion sickness mechanisms and physiology improves, self-ratings will remain the standard for calibrating any objective measure thereof.
- Much variability occurs in the physiological measures which have been tried, some of which can be explained by confounding factors, such as ambient temperature, airflow, clothing, rate of breathing, physical fitness, skin color, body size, age, state of circulatory health, digestive health, feeding stage, state of exertion, amount of body movement, and state of arousal, anxiety, fear, or stress. Symptomatology measures can be influenced by some of these confounds also, but the literature is filled with reports of physiological correlates that could be strongly confounded with factors other than changes in MS per se, such as eye strain as caused by accommodation-convergence conflicts (see Section 4.1). Overall, physiological findings in the literature have been mixed, and the significant correlations which have been observed are generally not large.
- Although correlations with motion sickness severity have been found, a major drawback of these physiological correlates is that they vary greatly between individuals and are not always stable between tests. Physiological measures, for example, tend to show lower test-retest reliability than self-report measures of motion sickness [49]. Also, Stout and colleagues [85] pointed out that, although physiological variables at the nausea endpoint (i.e., vomiting) are relatively stable between tests, temporal changes of these physiological measures in the course of these tests before reaching the endpoint were not. Multiple tests had to be averaged in order to find a correlation between subjectively rated misery and the (autonomic) variables measured. Data from Cowings et al. [100] imply that not all subjects have similar physiological response patterns, and certainly not all subjects display a similar relation between the response magnitude and the level of subjectively rated misery. The same authors indicate that these physiological correlates may serve as an additional measure to characterize motion sickness, but only together with subjective ratings.
- Several of the objective measures described are not (yet) applicable outside the laboratory. Measures taken with electrodes often suffer from motion artefacts, either due to insecure placement of electrodes onto the skin (further impeded by sweating), or by subcutaneous electromechanical effects. The latter seems specifically at issue with Electroencephalography (EEG) recordings.
- Any apparatus requiring (invasive) contact or interference with the subjects will impede application in real life conditions by imposing restrictions (e.g., to freedom of movement), causing distraction and discomfort, and disrupting activities. Given the interference required for rating sickness by subjective reports, it remains the question which method is preferred.
- Most raw physiological data require a certain degree of subjective judgment during the interpretation process, concerning eliminating of artefacts, choice of filtering frequencies, goodness of data, inferences concerning underlying processes, etc. One cannot simply equate physiological

measures with objective measures, especially since the majority of physiological studies of motion sickness have not been blinded.

- Physiological measures are usually more expensive, time-consuming, and subject to data loss than self-reports.
- It is illogical to assume that a few channels of physiological data are going to provide a richer understanding of a person's overall degradation of well-being than the person's conscious awareness of his state. For example, why would using a few electrodes to estimate stomach pacesetter contraction frequency provide a better indication of one's reaction to nauseating motion than the information coming to the person's brain via its thousands of natural connections to the gut?
- Even when multiple physiological measures are combined to give a more sensitive (e.g., Ref. [108]) and specific measure of motion sickness, very large numbers of observations would be required to find reliable predictors. Data fitting does require overdetermined systems (i.e., the number of equations or observations should be larger than the number of unknown parameters), and the variables observed should be uncorrelated, the latter in particular posing serious requirements to the conditions considered. If not reckoned, even a slightly different dataset can result in a completely different set of optimal parameters fitting the data. Concepts like constraint counting could be helpful in this respect. If, alternatively, machine learning or neural modelling were employed, possibly in combination with big data analysis, predictions might be improved but underlying mechanisms and causes would remain to be understood.

Ultimately, it does not benefit research science to assume that "objective" measures are superior to "subjective" measures. Rather, what scientists should seek, are measures that are reliable and valid (sensitive and specific), regardless of their type. Each type of measure has its unique advantages and disadvantages. Physiological measures are useful for exploring specific aspects of the motion sickness reaction (e.g., the quantification of pallor via skin measures), while behavioral measures are important for determining which aspects of subjective distress are associated with performance degradation. The best way to get a complete understanding of motion sickness is not via any single measure, but to employ appropriate self-report, physiological, and behavioral/performance measures together. Where all three types of measures yield concordant findings, more confidence exists in the validity of one's study.

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Chapter 5 – FACTORS IMPACTING CYBERSICKNESS

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5.1 INDIVIDUAL FACTORS IMPACTING CYBERSICKNESS

The comfort, performance, task completion, or training of some military personnel can be degraded during certain dynamic vehicle transportation operations, or during the use of simulators or virtual/augmented environments. The degree of sickening challenge posed by these situations will depend upon the characteristics of the stimulus (e.g., amount of real or visual motion triggering abnormal sensorineural integration, duration of exposure, display refresh rate, field of view) and the user's behavior within the synthetic environment (e.g., the number and type of head/body movements required to complete virtual tasks or locomote virtually). In addition, the **personal characteristics of the user** per se are important to consider. Different users are known to vary widely in their inherent susceptibility to simulator sickness and cybersickness, even when performing the same task using the same display. In fact, roughly two-thirds of flight simulator pilots or VR users experience no symptoms, while ~5% will experience **severe** symptoms [1], [2]. Are there individual traits or other reliable user characteristics which could be measured prior to exposure to predict which users will experience negligible vs. severe symptoms using the same device? This chapter seeks to answer that question. We start by defining the scope of individual characteristics that are appropriate to consider. We then introduce the many potential Motion Sickness (MS) and Visually-Induced Motion Sickness (VIMS) predictors or correlates that have been hypothesized in the literature. Finally, we evaluate the quality of the evidence for individual predictors of sickness and provide recommendations concerning the most promising user characteristics that might be worth assessing as predictors in the military setting.

5.1.1 Understanding the Scope and Dimensions of 'User Characteristics'

First, we must clarify what is meant by "user characteristics," because the most relevant hypothesized user characteristics in the literature are not necessarily immutable individual traits; in fact, they vary widely in terms of how trait-like (fixed) vs. changeable they are. For example, the degree of heritability of susceptibility from close family ancestors should be a relatively fixed predictor, barring epigenetic influences or variation in survey responses. Conversely, fairly malleable "learned" characteristics exist that can be acquired in hours or days, but nevertheless are considered **individual characteristics relevant for consideration** in this chapter **because they comprise a non-transient alteration in the user's intrinsic baseline susceptibility** which could be explored as a sickness predictor. Examples include the user's state of acquired stimulus habituation, or conversely, the user's state of acquired aversive conditioning due to past sickness experienced during exposure to similar stimuli. These malleable variables are also appropriate for exploration to determine if they are military-relevant user variables, because the purpose of such applied research is to exploit any user-specific variables to identify practical predictors of sickness, rather than to fully understand individual fixed traits, per se.

User characteristics also vary in how directly tied to susceptibility they are. There are some obvious, direct, and specific user characteristics for predicting individual susceptibility to an upcoming stimulus, such as the

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user's actual measured symptom severity during a prior exposure to the identical stimulus. Conversely, there are some more indirect predictors, such as one's visual field dependency score (see Section 5.1.4.2.6). This distinction is relevant to applied operational research, because whenever the literature findings are uncertain concerning two potential predictors, it will usually be more logical to explore the more direct predictor first. For example, indirect predictors will tend to have less face validity than direct predictors and more potential confounds to explore and resolve in order to interpret the reasons for a negative finding.

Finally, how fixed, **and** how direct a group of predictors are can **both** be considered and compared simultaneously. For example, a hypothetical sickness predictor such as symptom severity during a prior exposure is a far more direct yet malleable predictor than a hypothetical sickness predictor such as ethnicity (see Figure 5-1). In summary, a wide array of different variables could be called user characteristics and evaluated to determine whether they are useful for the prediction of sickness during exposure to visual-vestibular challenges. The unifying concept in the various cases considered in this chapter is that the focus of the individual research or theorizing we discuss is always centered upon the **characteristics the user brings into the virtual environment**, **prior** to the start of a given virtual interaction.

Figure 5-1 shows eight examples of individual characteristics (predictors of visual-vestibular sickness) that have been hypothesized in the literature, showing where they are estimated to lie on two continua: a) fixed trait vs. changeable state; and b) direct vs. indirect predictor of MS/VIMS.[2]

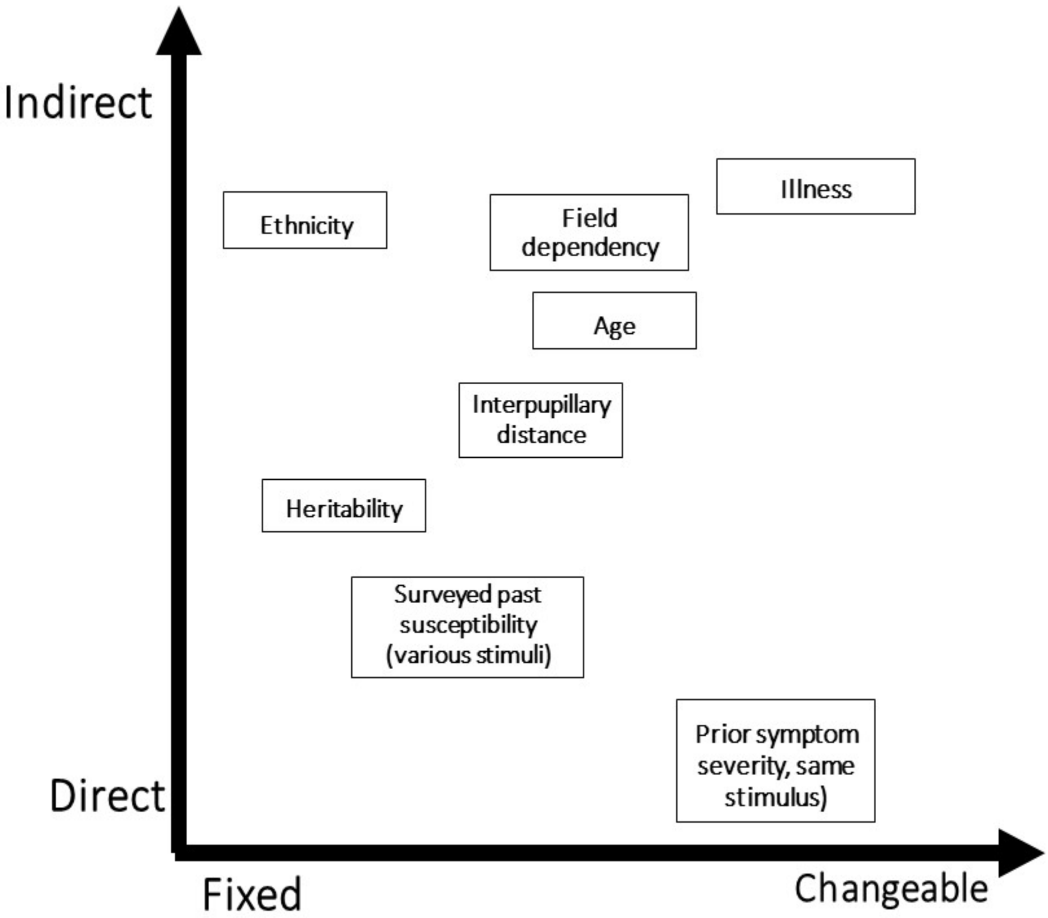

Figure 5-1: The Dimensions of User Characteristics.

[2] Note, however, that even relatively fixed traits may have interaction effects with variables that change over long periods of time, such as sociocultural influences, shared family motion experiences, or age.

5.1.2 The Need for Caution Concerning Military Recommendations Based Upon User Characteristics

There are dozens of individual characteristics the user brings to the simulator/VR/AR experience, many of which have been hypothesized at one time or another to be factors which might influence susceptibility to real or visual motion. Unfortunately, as with the rest of the general literature on human perception, performance, and user comfort, studies of **stimulus** effects upon sickness have tended to be more plentiful than studies of the influence of **individual characteristics**, so data and replications are limited concerning the contribution of inherent user traits in this domain, and many findings are mixed. Moreover, several important research limitations exist in the published literature concerning visual-vestibular experiments where strong adverse symptoms are elicited, including high intersubject variability in symptom severity, inadequate control for strong carry-over effects from one provocative session to the next (e.g., due to pausing for several minutes instead of several days between exposures), far too many small sample studies (partially due to the difficulty of recruiting and retaining subjects, especially for repeated measures), and incomplete data sets (due to subjects quitting or failing to return for a second exposure session). Some researchers have gravitated towards the use of milder stimuli which would appear to reduce some of the problems just mentioned. However, this approach has often merely raised other problems, as many studies in the literature have employed overly mild stimuli. As a result, a statistical difference in symptom severity across conditions is often reported in the literature in experiments where most of the subjects **were not really "sick**," i.e., a functionally-significant motion sickness discomfort level cannot be inferred confidently. Readers should be skeptical concerning any operationally-relevant generalizations made in cases where non-military subjects are exposed to stimuli far less sickening than those military personnel would experience during their duties.[3] This is especially true when the authors are making recommendations that might affect their own research programs, the career opportunities of military personnel (e.g., via job selection), the choice of sickness countermeasures that should be provided to service members (such as medications), or the best way to improve the displays they use for training and operations. To illustrate this important point with a hypothetical example, the most relevant question to the military is **not** likely to be whether an individual characteristic should be adopted as a predictor because a subject with that characteristic experienced a few non-nausea symptoms of minimal severity while those without that characteristic exhibited (a statistically lower finding of) only one non-nausea symptom of minimal severity. This would be a difference mostly of interest in the lab setting. Rather, operationally-relevant studies should be functionally meaningful and relevant to the target military operations, e.g., they should seek to determine whether a hypothesized predictor actually predicts greater-than-minimal severity nausea, and if so, whether perceived workload, situation awareness, task prioritization, or individual task performance gets worse.

An additional technical limitation is that many of the measures being correlated in this line of research have limited measurement reliability [3]. A final important limitation is that far more studies of motion and simulator sickness studies have been conducted than cybersickness-specific studies, as virtual and augmented environments only started to become common worldwide in the mid-2010s [2]. Because of this and the other limitations we have mentioned, conclusions should be made cautiously concerning the evidence for individual trait predictors of cybersickness. The present chapter emphasizes the **most conservative** inferences that can be drawn when several well-controlled studies have obtained the same strong finding, rather than to discuss every variable where a single positive predictor claim has been made. For this reason, the reader will find fewer emphatic conclusions in this chapter than are made about some of these variables in the rest of the literature. This conservative approach accords with the Popperian approach to science, and is especially fitting for a NATO report, since the applied-research focus of our NATO committee is to make effective and practical operational recommendations where there is a high degree of confidence concerning cybersickness prediction, prevention, or mitigations. This requires the identification of the most effective and proven solutions requiring the least time and cost to implement, while simultaneously preserving the maximal pool of eligible recruits for a given military occupational specialty.

[3] However, mild symptoms seen among military personnel doing duty-relevant tasks should be studied to ensure they do not alter their behavior in ways that would hinder good training transfer to the real situation.

Any other conclusions expressed in this report should be viewed with skepticism. Conservative conclusions are also important to avoid job assignments from occurring which are not firmly based upon one's ability to do the job whenever making decisions which incorporate demographic information such as sex, ethnicity, or age. Without appropriate caution, some military personnel could become stigmatized or incorrectly prevented from tackling a duty, mission, or occupational specialty at which they would have excelled. It is important to be able to predict those likely to be disturbed by unusual visual-vestibular stimuli and assist them, but it is equally important not to reject someone who might later prove to be the next Eddie Rickenbacker or Horatio Nelson[4]. In fact, no demographically-based information in this report should be implemented without first consulting the equal opportunity and legal representatives of the nation(s) concerned. With these important caveats in mind, we turn next to a brief accounting of the many sickness predictors which have been hypothesized in the past literature, a few of which are promising for military application.

5.1.3 Overview of Candidate Predictors of Individual Susceptibility Hypothesized in the Literature

Numerous potential predictors of individual susceptibility have been hypothesized in the literature. A summary is provided in Table 5-1, along with our judgement of whether the stated variable is a likely predictor of sickness. (The literature is discussed after the table). Readers will note that while most of these factors are possible predictors, only a few factors are judged to be highly likely predictors backed up by sufficient evidence.

Table 5-1 lists twenty-five potential user characteristics from the literature which have been hypothesized to predict motion sickness or visually-induced motion sickness. Most are not yet proven definitively.

Table 5-1: Potential Predictors of Individual Susceptibility.

Potential Contributor	Is an Effect Likely? (No, Possible, Probable, Yes)	Quality of Evidence Concerning Effect (Limited, Mixed, Moderate, Good)	Further Discussion in this Report?
Past response: General/retrospective (MS history survey)	Yes	• Good evidence of usefulness, despite potential for social desirability to be a confound during self-reporting. • Some military-relevant normative data exists but not a full database of NATO norms.	Yes
Past response: Empirical (during past transportation stimulus)	Yes	Moderate evidence of prediction between similar vehicle transportation types, with promising meta-analytic findings; further evidence should be obtained.	Yes
Past response: Empirical (during lab stimulus)	Yes	Good evidence: many studies have been done, but not every lab stimulus is predictive of every target real/visual motion situation.	Yes

[4] Biographers have noted that U.S. Army Air Service Captain Rickenbacker suffered from airsickness initially but went on to become the greatest American Ace of WWI. Royal Navy Vice Admiral Nelson suffered from periodic seasickness throughout his unparalleled career.

Potential Contributor	Is an Effect Likely? (No, Possible, Probable, Yes)	Quality of Evidence Concerning Effect (Limited, Mixed, Moderate, Good)	Further Discussion in this Report?
Heritability: Past response of close relatives or genetic predisposition confirmed empirically	Probable	• Limited Studies. • Some confounds related to shared family experiences whenever reasoning beyond identical vs. fraternal studies. • Social desirability could be a confound during self-reporting.	Yes
Level of experience: Habituation, adaptation	Probable	Moderate specific evidence but good general evidence. Recent evidence of video game play predicting lower cybersickness [4] (viz., experience with VR or dynamic video games) could prove interesting in future, as a similar variable was useful in a cybersickness history survey development effort [5].	Yes
Plasticity (ability to adapt)	Possible	Limited evidence, but logical assertion	No [3], [6], [7]
Field dependence/independence	Possible	• Moderate evidence. • Mixed and complex findings, which nevertheless emerge as somewhat promising in meta-analyses.	Yes
Anxiety/Personality	Possible (Not possibility for stigmatization)	• Mixed findings. • Several confounds. • Nevertheless, strong state anxiety can elicit nausea by itself, which exacerbates overall/cumulative discomfort via mechanisms other than visual-vestibular.	Yes, briefly
'End organ response' e.g., vestibulo-ocular reflexes	Possible	• Mixed findings; some confounds. • Many types of responses to explore; estimate of effect and evidence varies with the specific measure. One meta-analysis [3] did not rate this approach highly in general, but a more recent paper [8] endorsed a relation between a specific variable (semicircular canal velocity storage) and MS in parabolic flight.	Yes, briefly

Potential Contributor	Is an Effect Likely? (No, Possible, Probable, Yes)	Quality of Evidence Concerning Effect (Limited, Mixed, Moderate, Good)	Further Discussion in this Report?
Migraine/history of headaches	Possible	Several studies but need for greater synthesis of findings.	Yes
Aerobic Fitness	Possible (Note possibility for stigmatization based on body appearance)	• Limited direct longitudinal research. • Potential confounds include age, arousal level, experience. • Possible limited applicability to a population already within a narrow fitness range.	No [9]
Age	Possible (Note possibility for stigmatization)	• Limited Studies. • Effect Not simple. • Mixed findings from cybersickness. • Age range restricted in most empirical studies looking at age post hoc. • Some confounds related to habituation, vestibular disorders, ocular disorders, subsequent avoidance of motion, etc.	Yes
Sex	Possible, but not proven (Note possibility for stigmatization)	• Mixed findings in overall literature. • Limited and mostly negative findings from controlled lab studies. • Many confounds. • Alternative explanation identified recently for observed sex differences in cybersickness. • Questioned in recent systematic reviews or meta-analyses.	Yes

Potential Contributor	Is an Effect Likely? (No, Possible, Probable, Yes)	Quality of Evidence Concerning Effect (Limited, Mixed, Moderate, Good)	Further Discussion in this Report?
Ethnicity	Possible; not proven (Note possibility for stigmatization)	• Limited studies, only one of which separated ethnicity from country of residence. • Limited ethnicities observed so unable to generalize to ethnicity per se. • Numerous confounds, including heritability, sex, culture, habituation, experience.	Yes
Inter-Pupillary Distance	Possible	Limited	Yes, briefly
Flicker Fusion Frequency Threshold	Possible	Limited	No [10], [11], [12]
Mental Rotation Ability	Possible, not proven	Limited	No [13]
Postural Stability	Probable for postural aftereffects. Possible for baseline postural sway.	• Moderate: A fair amount of evidence for postural effects after exposure. • Many studies for instability as a predictor but findings mixed across labs and some controversy on this point.	Yes, briefly
Vection Illusion (susceptibility/strength)	No	• Moderate. • Mostly negative findings, despite frequent conjectures of a relationship in the literature.	Yes
Illnesses	Possible	Limited direct evidence, but logical hypothesis as another pathway to nausea exacerbating cumulative discomfort.	Yes
Visual Disability	Possible	Limited	Yes
Body Mass Index	Possible, unproven (Note possibility for stigmatization)	Limited	No [14]

Potential Contributor	Is an Effect Likely? (No, Possible, Probable, Yes)	Quality of Evidence Concerning Effect (Limited, Mixed, Moderate, Good)	Further Discussion in this Report?
Concentration Ability	Possible, unproven	• No trait evidence. Trait hypotheses could be developed from indirect, limited evidence regarding state distraction, studied via tasks or music. • Distraction state research confounds include visual cue effects [15] or mood effects [16]. Fewer confounds in Ref. [17], but small effect size of task during a stimulus not eliciting nausea.	No [15], [18], [17]
State of classical/aversive/operant conditioning	Probable; not fully proven	Limited specific evidence concerning cybersickness, but logical assertion and good general evidence concerning nausea and motion sickness [19].	Yes, briefly

5.1.4 Individual Consideration of a Few Selected Candidate Predictors

It is not within the scope of this chapter to review the literature evidence for every one of the hypothesized twenty-five candidate predictors in Table 5-1. Rather, we will highlight those variables from Table 5-1 that meet either of the following negative or positive selection criteria:

- Negative Selection Criterion: The variable is **often mentioned** in reviews **as a predictor**, **but the confirming evidence actually is not sufficient**, and/or there is a reason why the **usefulness of the variable would be limited in the military setting**. In this case, it is important to mention the variable so that military researchers, trainers, and decision makers do not waste time and money developing solutions that are less likely to work for the military.
- Positive Selection Criterion: The variable is one of the candidates on the list that is most **likely to work for predicting sickness** and would be **feasible to implement in a military setting** (e.g., retrospective survey concerning past responses to visual or real motion). In this case, it is important that the military knows about the most promising candidate predictors, so that further studies can explore their utility for possible implementation in the military training, simulation, and performance augmentation settings.

5.1.4.1 Problematic Predictors Reported to be Useful but which Have Important Scientific or Military Limitations

5.1.4.1.1 Age: A Possible but Not Straightforward Contributor with Some Limitations for Military Application

Age has a non-linear relationship with MS susceptibility. Children less than 2 years old or younger may not be susceptible to motion sickness, but sensitivity increases steadily until age 10 – 12, and then declines gradually for the rest of one's life (with the possible exception of one's elderly years) [1]. A retrospective motion history survey study [20] reported a significant effect of age on motion sickness among subjects ranging from 20 – 92 years old and comprised of two groups of mean age 52.9 ± 19.2 and 66.3 ± 14.5). However, military-relevant generalizations cannot be made from motion sickness trends among children and elderly people, or from the aforementioned study wherein the mean age was 54 or greater. The median age of active-duty U.S. servicemembers is 27 [21], and about two-thirds of them are age 30 or younger [22]. These younger servicemembers are also represented in large numbers in training and selection pipelines soon after their enlistment.[5] Therefore, the question of relevance when considering whether age-related prediction of motion sickness susceptibility is useful in the military setting is **not** whether an age correlation exists, but rather, whether it is predictive within a **much narrower** age range, such as 18 – 30. The evidence concerning this question is limited. A study [23] looked at 246 non-military subjects with a mean age of 36 (SD 11.3). The purpose of this study was to determine whether a retrospective motion sickness history questionnaire could predict actual reported symptoms during the highly sickening conditions of parabolic flight. The confounding effects of specific motion experience were reduced by analyzing only the subjects who had no prior zero-G experience (n = 81, M 32.1, SD 9.2[6]). This revealed a medium correlation between age and sickness ($r = -0.36$, $P < 0.001$), albeit the age vs. MS correlation failed to be significant (or to reach a small effect size) when looking only within the subgroup that was less than 30 years old.

From these findings, we infer that scientific exploration of age as a motion and visual motion sickness predictor is warranted in studies of active-duty subjects, but we cannot recommend the near-term implementation of age as a practical way of distinguishing the likelihood of motion sickness among the majority of active-duty servicemembers. Furthermore, since highly experienced pilots (who tend to be older than new pilots) are more susceptible to flight simulator sickness [24], age alone may not be a reliable predictor in a military setting, unless simulator/virtual environment-specific **experience** (leading to adaption/habituation) is known as well.

Finally, in the context of the present chapter's focus upon visual displays, it is important to determine whether age-related susceptibility trends for VIMS follows the same pattern as trends for MS. Some studies report this is so [25], [26], while other studies do not find sufficient supporting evidence or report opposite trends [27], [28], [29], [30], [31]. These literature trends reinforce our recommendation to refrain from adopting age as a confirmed VIMS predictor without obtaining more clear research-based evidence first. Moreover, socially sensitive, and historically misused personal characteristics such as age, sex, or ethnicity require unassailable proofs before adoption as decision criteria, so as to avoid stigmatization or discrimination (see Section 5.1.2). Should such characteristics be proven sufficiently at a later date, they should be used in isolation, and should be used to inform MS/VIMS mitigation strategies and countermeasures, rather than selection decisions.

> ***Recommendation:*** *Age is easy to track and possibly useful, so it should be explored post hoc as a potential covariate of sickness in the military setting, but it should not presently be adopted as a primary sickness predictor or decision criterion in an active-duty operational context.*

5.1.4.1.2 Sex: A Presently Unproven Contributor with Concerning Confounds

A common assertion one sees in the literature is that women[7] are more susceptible than men to experiencing sickness during exposure to real or visual motion (e.g., Ref. [16]). However, Lawson [1] questioned whether this assertion has been adequately established in the literature. He located more relevant studies than any published review but found that only 28/56 (50%)[8] of the relevant motion, simulator, VIMS, or VR studies

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[5] Note that the maximum age of initial enlistment varies across the services of each nation and the military branches within each nation, but generally ranges from the late 20s to the late 30s for active-duty service.

[6] According to Ben Lawson's personal communication with John Golding, 27 Feb 2021.

[7] Findings stated throughout this section concerning "women" are restricted to the most common genetic birth case of having no Y chromosome present among a complement of 46 chromosomes. This chapter is not intended to generalize to other genetic birth cases or to topics such as sex reassignment or gender identification.

[8] The true proportion of studies finding women more susceptible is likely to be lower than 50%, due to the well-established tendency for positive findings to be published more often than negative findings.

located yielded results clearly indicating that women were found to be significantly more susceptible to motion sickness than men. He concluded that this was not sufficient evidence to permit a confident assertion that women are more susceptible. His 2014 evidence is currently being updated with many more articles (Lawson, in preparation). The preliminary evidence obtained so far does not imply that a change in Lawson's [1] earlier conclusion is likely. For example, a preliminary evaluation of the 2019 – 2020 literature done for this NATO report revealed that no more than ~33% of the relevant studies in the last two years could be considered as finding women to be more susceptible, which, if borne out by the literature update, would lower the original 2014 estimate of 50%.[9] Of particular interest for this NATO report on cybersickness is that all the relevant 2019 – 2020 studies employed a vision-centric stimulus such as simulator or VR. Finally, mixed effects of sex were found recently in a meta-analysis of 40 motion/simulator/cybersickness studies [32], and a systematic review of 24 cybersickness experiments [33] concluded that only 5/24 studies observed women to clearly have higher susceptibility to discomfort while using VR.

Not only does the literature fail to convincingly establish that women are proven to be more susceptible to motion sickness than men, but it also contains several concerning confounds and trends which should make scientists reserve judgement on the issue for now. For example, women are more likely to be reported as more susceptible (than men) in lower-quality studies where fewer interpretation confounds were controlled, e.g., where the study was a survey rather than a controlled laboratory study [1]. Finally, women are more likely to be found more susceptible if the study was done ~40 – 80 years beforehand [1], implying a chronological bias may exist (e.g., a confirmation bias caused by the formerly-common societal belief in female sensitivity or fragility among experimenters and even among women subjects). Given these trends and the fact that women have been treated unfairly in the past, special caution is warranted concerning this variable. Socially sensitive and historically misused personal characteristics such as sex, age, or ethnicity require unassailable proofs before adoption as decision criteria, so as to avoid stigmatization or discrimination. Should such characteristics be proven sufficiently at a later date, they should be used in isolation, and should be used to inform MS/VIMS mitigation strategies and countermeasures, rather than selection decisions.

An important training consideration for women is that cybersickness is worse when the VR cannot be properly adjusted to fit the user's interpupillary distance. While this observation would apply to a man or a woman, it occurs more often due to a short interpupillary distance, and therefore is more common among women because their bodies are smaller, on average [14]. VR design improvements are recommended to eliminate this problem for all users. Until such improvements are made, trainers should be sensitive to the needs of trainees of smaller stature, e.g., by warning them when a perfect fit has not been obtained and encouraging them to request a training pause if needed.

> ***Recommendation:*** *Sex has historically been easy to track as a covariate and any sex-based influences are important to know about, since women represent 50% of the population of potential military recruits. Sex should be studied further in the research setting via controlled laboratory studies with the numerous confounds better controlled than in most past studies. Presently, sex should not be viewed as a primary predictor of sickness, nor adopted as a decision criterion in the operational setting.*

[9] Nine more relevant studies were located (published Jan 2019 to April 2020) failed to find women more susceptible and 3/9 had mixed positive findings. If three studies are liberally counted as having found women more susceptible, the proportion would be 33%. Adding the Lawson [1] findings to the 2019 – 2020 findings, the revised proportion = 31/64 studies (48%).

5.1.4.1.3 Ethnicity: A Possible but Socially Sensitive Contributor Requiring More Evidence

Asians have been reported to be more susceptible to visually-induced motion sickness than European-American and African-American[10] [34]. Tibetans and Northeast Indians also have been reported to be more susceptible to motion sickness Northwest Indians.[11] Another large sample lab motion study showed that 82 Chinese subjects were significantly more susceptible (than 227 Caucasians of mostly European origin) to a very brief (5-minute session) of a widely employed simultaneous multi-axis rotation stimulus known as Coriolis cross-coupling [35]). The sickness severity levels reached in this study were not described, so it is not possible to infer the overall functional significance of the findings. However, the study corresponding author Dr. Enck[12] recollected that average sickness was not severe, albeit some participants got quite nauseated. Variations in MS susceptibility that are intended to generalize to the main ethnicities among military personnel of NATO countries have not been developed. As numerous cultural differences exist concerning gender norms, patriarchy, opportunities for exposure to challenging forms of transportation, and male willingness to exhibit 'weakness,' we recommend against making ethnic generalizations or strictly genetic interpretations concerning these trends. Socially sensitive and historically misused user characteristics such as ethnicity, sex, or age require unassailable proofs before adoption as decision criteria, so as to avoid stigmatization or discrimination. Should such characteristics be proven sufficiently at a later date, they still should not be used in isolation, and should be used to inform MS/VIMS mitigation strategies and countermeasures, rather than selection decisions.

> ***Recommendation:*** *A wider range of ethnicities should be assessed further via controlled laboratory studies, but ethnicity should not be viewed as a primary predictor or decision criterion in the operational setting. Given historical and cultural considerations, ethnicity-based decisions should be made with the utmost caution.*

5.1.4.1.4 Postural Stability: A Possible but Complex Contributor

Postural stability is the ability of an individual to balance and avoid discoordination or falling while standing or locomoting. It relies on input from the visual, somatosensory, and vestibular systems. Stimuli triggering unusual integration of current or stored visual, vestibular, and/or somatosensory inputs can cause postural instability as well as motion sickness. Level of post-exposure ataxia is likely a function of several factors including the duration of the exposure, the individual's level of VR experience, and the task performed in the VE. For instance, repeated exposure to a simulator leads to a sickness decrease over time but an increase in ataxia, most likely due to adaptation aftereffects upon returning to the normal visual-vestibular cues and gravitoinertial force environment [12], [36]. While trainers and trainees should be made aware that postural instability can occur following simulator sickness, there is controversy concerning the extent to which more subtle baseline levels of postural sway in healthy people predicts who will subsequently be susceptible to visually-induced or motion-induced sickness, or how reliably postural instability temporally predicts sickness onset or severity during exposure [37]. One problem is that the key criteria have varied from study to study, with the observations deemed worthy of rejecting the null hypothesis (viz., that sway does not temporally predict MS) having included increased sway, decreased sway, increased variability of sway, etc. [37]. To better understand the potential role of postural instability as a cause rather than an outcome of MS/VIMS, postural stability should be assessed during controlled studies in the laboratory research setting where gold standard postural equilibrium assessment equipment and best-practice measures are employed, functionally sufficient sickness of known severity is elicited, a consistent a priori criterion for postural disequilibrium is established and employed from study to study, double-blinding to study hypotheses is ensured, the stimulus presented to subjects is controlled and replicable, arousal/anxiety-related state or trait

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[10] Stern et al. [34] described two studies employing treatment groups composed of 1) 15 Chinese-born women; and 2) 30 Chinese-/Taiwanese-/Korean-Americans of unspecified sex. (A third group of 15 Chinese subjects (10 of whom were women) was studied without comparison to other ethnicities.

[11] The specific differences observed in this study would be of limited utility to NATO.

[12] Ben Lawson's personal communication on 3 March 2021.

influences are controlled and monitored, and the influence of respiration on observed sway is assessed [1], [37]. Established symptom measures such as the Simulator Sickness Questionnaire / Motion Sickness Questionnaire [38] should be employed in all such studies as well, to aid cross-study comparison and permit the graded estimation of more than one sickness severity level. By widespread adoption of these procedures, a better understanding can be developed which accounts for the most troublesome observations in this area of inquiry (Section 23.91 in Ref. [1]). Studies meeting these criteria will, of course, be of greater applied utility if they employ stimuli and tasks relevant to the military and establish predictive validity relative to operational scenarios and outcomes.

> ***Recommendation:*** *Postural stability should not presently be adopted as a primary predictor or decision criterion in the operational setting. However, since postural ataxia can be hazardous with or without MS/VIMS being present, this problem has practical importance outside of the scope of the present chapter. Therefore, cases of dizziness, vertigo, ataxia, or falling after the use of a simulator, VR, or AR should be documented carefully for exploration of patterns which could aid training safety.*

5.1.4.1.5 Vection Susceptibility/Strength: An Unproven Contributor

Since subjects vary in how quickly they experience the onset of the illusion of self-motion (vection) while viewing visual field movement, it is hypothetically possible that such individual variation in vection strength constitutes a nontransient user characteristic akin to a vection susceptibility trait. While this notion is not proven, it is reasonable to conjecture, since people differ in their inherent degree of visual dependency and field dependence (see Section 5.1.4.2.6 below on field dependence and visual dependency), and individual proclivity for vection is moderately stable [39].

Unfortunately, the relationship between the state of vection and the elicitation of VIMS is also unproven. It is common to read reviews that mention the presence or strength of vection as a likely state predictor, correlate, or cause of visually-induced motion sickness, with Hettinger et al. [40] often cited as the original paper hypothesizing this relation in a synthetic display setting. It should be noted, however, that the original report by Hettinger et al. was merely raising an interesting possibility for exploration, based on a correlation that was not detected as significant.

Theoretical questions arise also concerning vection state as a cause or exacerbator of VIMS. Since the vection illusion is enhanced by reduced sensory conflict, it could be argued that vection constitutes a viable perceptual **solution** for a visual-vestibular conflict rather than an exacerbator of such conflict [41]. Therefore, adherents of the sensory conflict hypothesis of motion sickness causation could argue that increased vection should correlate with **lesser** (rather than greater) sickness, which was observed in a recent VIMS study described in Ref. [2].

In addition to theoretical problems concerning why vection would be predicted to cause MS/VIMS, and the empirical counter case cited above, there are additional empirical findings that do not support the argument. It has been known since one of the earliest studies of vection vs. VIMS [42] that VIMS can be reported by subjects experiencing no vection. Conversely, it has been demonstrated that careful control of the visual stimulus can elicit near-maximal ratings of vection with negligible ratings of VIMS [43]. These and other studies indicate that vection is neither necessary nor sufficient for VIMS to occur. In fact, it appears that only a minority of published VIMS studies have detected any significant relation between vection and VIMS [1]. For these reasons, there is presently no firm theoretical or empirical basis to assert that vection state is a useful predictor of VIMS. In fact, while visual flow *per se* can be sickening, it is possible that proper design of the moving visual stimuli (e.g., by appropriate control of the direction, timing, duration, velocity, and type of visual flow) will permit the exploitation of vection as a **useful adjunct** to the virtual experience. When the visual stimulus is controlled properly relative to the user's head movements and virtual locomotion techniques, vection can serve as a relatively easy, inexpensive, and small-footprint way to introduce a compelling feeling of self-motion through the virtual world. This could make the experience more immersive and more representative of the natural sensations one has when moving through the real world. In fact, no matter how realistic visual and auditory displays become in the future, users will never feel that a virtual experience involving avatar motion through the virtual world is indistinguishable from the comparable real-life experience unless compelling self-motion sensations are incorporated into the VR via the application of real or apparent motion cues [41].

> ***Recommendation:*** *The strength of one's illusion of self-motion (vection) should not be assumed to be a user trait and experiencing a state of vection should not be viewed as a proven sickness predictor or decision criterion in the operational setting. However, due to its potential practical benefits as an induced state, vection should be explored in the research setting to determine its interaction with tactile/kinesthetic cues, and its relation to variables such as comfort, immersion, presence, situation awareness, task performance, willingness to use a training device, and degree of training transfer to real situations.*

5.1.4.2 Individual Characteristics Most Promising for Further Evaluation in the Military Setting

5.1.4.2.1 Past Motion Sickness Response: A Useful Predictor with Moderate-to-Good Evidence

The most logical and direct candidate predictor of a person's MS susceptibility to a given stimulus is that person's measured past response (i.e., MS severity score) during exposure to the same or a similar stimulus (e.g., predicting later airsickness based on prior airsickness). This and other, less-direct estimates of past MS susceptibility in comparable situations (e.g., predicting airsickness from seasickness, or from laboratory MS[13] or from recollected MS in a survey of past motion situations) have been evaluated in numerous studies reviewed by Kennedy et al. [3], and summarized in this paper. These approaches have been found to be more promising than most other candidate predictors, with the greatest amount of evidence having been amassed for the usefulness of MS history surveys, because they are easier to administer than actual motion exposures, and because they are often administered alongside studies involving actual motion exposures (as an additional source of data, a subject selection criterion, or a covariate for refining the analysis). One of the most commonly-employed history questionnaires currently is the Motion Sickness Susceptibility Questionnaire (MSSQ), in its regular or short version [16], which is described in more detail in the description of symptom measurement in Chapter 4 of this Technical Report. The MSSQ was originally developed in the military setting (at the Royal Air Force Institute of Aviation Medicine), partly using military participants. While it does not have access to a large normative database concerning NATO military service members, several studies have gathered data permitting the main proponent of the MSSQ to quantify any respondent's scores against smaller groups of relevance14, such as U.S. Navy aviation personnel [44] and French aerobatic pilot students [45]. A recent version of the MSSQ tailored for VR has been developed recently [5].

Tracking MS response to the same operational situation the optimal approach [3] and is concordant with U.S. military practice in the aviation training setting, wherein airsickness exhibited during early in-flight training is an important basis for decisions about whether an aviation candidate should:

a) Continue flight training with no MS countermeasure;

b) Be allowed to take approved medications for the first few flights; or

c) Undergo a prolonged hiatus to engage in airsickness desensitization training.

13 This refers to measurement of severity of MS symptoms using an established scale and a controlled laboratory motion and/or visual stimulus whose severity is known.

14 Ben Lawson's personal communication with John Golding, 8 March 2021.

Finally, MS/VIMS prediction based on one's measured response to a comparable stimulus has the advantage of supporting egalitarian policies better than predictive strategies which rely upon demographic information such as age, sex, or ethnicity.

> ***Recommendation:*** *Indicators of severe MS/VIMS during past exposures to the same or similar situation (to the one targeted for prediction) should be considered the primary user-related characteristics for further NATO research and development. They should be the focus of individual differences research in the laboratory and operational settings. Where direct assessment of past response is not feasible (due to time or cost constraints), MS history surveys should be administered to establish group-specific norms and identify people who may require targeted interventions.*

5.1.4.2.2 Genetic Heritability: A Probable Contributor Requiring More Evidence

Limited but promising results imply the existence of a genetic contribution to motion sickness susceptibility since monozygotic twins react much more similarly (nearly a 0.70 concordance) vs. than dizygotic twins. [46]. Similarly, a genomic study found a relation between certain single-nucleotide polymorphisms and survey-reported carsickness susceptibility [47]. Genetic heritability is a logical variable to study for sickness prediction, albeit when it is done via questionnaires, they would need to be designed to avoid and detect social desirability confounds. It is possible that a rapid and inexpensive genetic test with good properties for predicting motion sickness susceptibility will be disseminated widely in the near future, which could become an important tool. Presently, more evidence and development are needed for such tests to become practical. (For example, one of the studies cited above only involved women.) Also, concerns have been raised in recent years concerning the potential for misuse of genetic data.

> ***Recommendation:*** *Heritability and genetics should be explored as predictors in the laboratory and field settings, especially in situations where the confound of social desirability of reporting can be controlled or reduced. Heritability should not presently be used as a decision criterion in the operational setting, but it should be researched alone and as part of multivariable predictive models of sickness, especially during high-stakes operations (e.g., vehicle delivery of special operations forces, astronauts, and space force operations). If predictive genetic tests become available, their usage and data access should be strictly controlled for the protection of service members.*

5.1.4.2.3 Visual Disability: A Possible Contributor Requiring More Evidence

It could reasonably be expected that VR/AR users with poor binocular function (due to convergence problems) would experience more oculomotor side effects than individuals with good function [10], apart from the aforementioned concerns about the need to fit the interpupillary distance of the user well. A history of visual difficulties may also be a caution against a possibly greater risk of oculomotor symptoms [10]. However, severe visual disfunction will be disqualifying for most military occupational specialties, so this factor is less applicable to an active-duty population. Moreover, while VIMS has many visual symptoms of interest, it is not a visual malady *per se*, but rather, a malady associated with poor multisensory integration of unusual inputs.

> ***Recommendation:*** *Aspects of visual functioning should continue to be assessed and explored as possible correlates of cybersickness but should not be considered a primary predictor or operational decision criterion until further evidence is obtained.*

5.1.4.2.4 Illness: A Possible Indirect Contributor Requiring More Evidence

Anyone suffering from fatigue, sleep loss, head colds or any respiratory illness, ear infections, hangover, upset stomach, or emotional stress may exhibit more adverse symptoms than when in their normal state of health. Use of alcohol or even some medications, or having received a recent immunization, can cause symptoms. While such ill states may not directly change a person's sensitivity to visual or real motion *per se*, they may contribute to more symptoms cumulatively via different pathways, thereby making the person more likely to experience more discomfort in a motion situation [48]. Therefore, it is common to see the recommendation that ill people should avoid using VR or simulators [10], [12], [49], [37]. Consequently, it is recommended that VR participants be screened before exposure to ensure that they are in their usual state of health [10].

> ***Recommendation:*** *Illness should be assessed and explored as a decision criterion (e.g., postponing individual training), for reasons of general comfort rather than as a specific predictor of motion sensitivity.*

5.1.4.2.5 State of Habituation/Adaptation: A Probable Contributor Requiring More Evidence

Users generally are less likely to develop MS/VIMS as they develop familiarity with a challenging situation, provided that the stimulus is not severe enough to cause aversive classical conditioning. Repeated exposure builds a tolerance to sickness-inducing stimuli and also give the user time to learn adaptive behaviors that minimize adverse effects [25], [50], [51]. It has been asserted that habituation (e.g., as reflected by increasing minutes of tolerance of a given stimulus) is one of the better predictors of the VIMS response [32]. While it is logical to predict a strong effect of the user's state of specific stimulus habituation/adaptation prior to exposure and this is considered an important method for building tolerance to VR [7], further studies are needed.

> ***Recommendation:*** *Habituation should be assessed and considered a likely predictor of an individual's response. Concluding that an individual is not able to tolerate a display should, when feasible, only be done when the person has had an opportunity to experience multiple exposures.*

5.1.4.2.6 Field Dependence/Independence: A Possible but Complex and Indirect Contributor

Field dependence/independence is a measure of cognitive-perceptual style [52]. Considered from a perceptual perspective (which is how it is measured), field dependent people are believed to rely more upon external cues (such as visual frames of reference) compared to internal cues (e.g., vestibular, and kinesthetic). While the literature [53] sometimes shows an interesting relationship between field dependency and motion sickness, the observed (and even hypothesized) direction of that relationship is not always consistent. Long et al. [54] found a significant relationship between greater field dependence and MS, while Barrett and Thornton [55] and Barret et al. [56] found field independent people to be more susceptible to VIMS. No meaningful relationship was detected by Barrett et al. [55] or two other studies [57], [45]. Frank and Casali [58] re-evaluated the evidence available at the time and concluded that there was little convincing evidence that field dependent people are more susceptible than field independent people. However, a review by Barrett [10] sought to explain the mixed findings by arguing that the people most susceptible to simulator sickness are **between** the two extremes of field dependence/independence. Furthermore, since three meta-analyses described in Section 5.1.5 [3], [32], identified field dependence/independence as a phenomenon of interest, it cannot be ruled out presently.

Since measuring field dependence requires time and the use of special equipment, practical considerations are important also. Field dependence will probably only be useful in the military setting in cases where the potentially minor improvement of prediction outweighs the minor costs of testing (which may be the case for military occupational specialties filled by small numbers of people and incurring high per-person training costs).

An analogous perceptual proclivity to field dependency is visual dependency, which is the over-reliance on visual cues by some types of vestibular patients. This could be especially important for stimuli causing VIMS. Several authors have asserted that visually-dependent patients are more likely to experience symptoms caused by visual motion [59], [60], [61]. For this reason, military clinicians and trainers should be watchful for inner ear infection, concussion, migraine, and other maladies which may alter visual-vestibular functioning. Moreover, researchers studying field dependency should determine whether greater field dependency predicts greater VIMS but not greater MS.

> ***Recommendation:*** *Field dependence should be considered a possible but not a primary, direct, or even straightforward predictor. It should be explored further as an adjunct measure (e.g., supplemental to measures of past severity of MS in comparable situations) in those research and operational situations where the need for optimal prediction accuracy is high enough to justify the equipment, time, and expertise needed.*

5.1.5 Systematic Findings from Meta-Analytic Comparisons of Candidate Individual Predictors

So far in this chapter, we have made recommendations based upon narrative interpretation of the literature concerning each candidate predictor. We now turn to more systematic findings from meta-analyses of multiple candidate predictors across the literature. One of the most comprehensive attempts to evaluate individual motion sickness predictors was performed by Kennedy et al., 1990 [3]. Based upon their collection of more than 2,000 motion sickness publications, they examined more than 100 potentially-relevant articles and then narrowed down the key predictors in more than 60 published studies they listed in their paper. They estimated the strength of numerous potential predictors from the literature, and their findings are summarized in Table 5-2. Three main inferences can be drawn from the variables assessed in Ref. [3]:

1) Measures of a person's past motion-related symptom severity was the best type of predictor of later symptom severity. Specific examples included:
   a) Predicting sickness severity in a given transportation situation based upon past reaction to that same situation. (Further, separate studies for meta-analysis would be beneficial here).
   b) Predicting from one transportation setting to a different one. (More studies would be beneficial.)
   c) Predicting from a sickening lab test to a transportation situation.[15]
   d) Predicting from recollected history of response in various situations to actual response during a specific situation. (Many studies and a large sample increases confidence here.)
2) In general, various psychological traits and baseline physiological measures accounted for little variance in motion sickness severity, albeit perceptual style and measured by field dependence appeared to be worth further exploration.[16]

Table 5-2 refers to meta-analytic evidence concerning the performance of six categories of sickness predictors (adapted from Tables 4-7 and 10 of Ref. [3]). The top two predictors entailed direct assessment of severity of symptoms during a provocative stimulus.

[15] While it is common for laypeople to assert that lab tests are not useful for predicting sickness in other situations, Kennedy et al. [3] noted a median observed predictor correlation of r = 0.38 (estimated across more than a dozen studies), and prediction is likely to be even better if one is not looking for an overall correlation, but rather, a way to identify the 5% of the population who are highly susceptible to a wide variety of MS/VIMS triggers..

[16] While field dependence has the potential to account for up to 26% of corrected variance, it should be noted that three field dependence studies in Kennedy et al. [3] were rod-and-frame tests and three were embedded figures tests, with poor results from embedded figures studies. Also, the direction of observed correlation was negative in 1/3 rod-and-frame studies and positive in the other two (albeit absolute correlations ranged from |0.37| to |0.46|).

Table 5-2: Meta-Analytic Evidence Concerning the Performance of Six Categories of Sickness Predictors.

Predictor Category	Predictor Type	(Ideal Corrected[17]) Variance in MS/VIMS Accounted For[18]	Literature Basis (Quality of Evidence)	Example of a Predictor Assessed
Past Symptom Response vs. Future Symptom Response	1) Transportation	67%	4 studies comprising >2,000 subjects total	Airsickness (early vs. later in training or vs. other transportation)
	2) Laboratory	38%	13 studies comprising >1,000 subjects[19]	Brief Vestibular Disorientation Test (vs. later airsickness or another lab test)
	3) History	34%	23 studies comprising >3000 respondents	Motion History Questionnaire (vs. various transportation settings or lab tests)
Psychological	4) Perceptual Style – Field Dependence	26%	6 studies comprising >200 subjects. [20]	Field independence tests (vs. simulator sickness or motion history)
Psychological;	5) Personality *(tied with…)*	7%	7 studies comprising >400 subjects	Neuroticism (vs. motion history)
Physiological	6) 'Autonomic'	7%	13 studies comprising >200 subjects	Adrenocorticotropic hormone (baseline vs. lab motion test)
'End Organ'	7) 'End organ'	6%	11 studies comprising >600 subjects	Postural stability (vs. motion history but not parabolic flight)

The Kennedy et al. [3] findings were of great practical benefit for operational settings, since they indicated that a short motion sickness history questionnaire plus simply tracking a service member's initial response to the provocative situation of interest (e.g., a required flight simulator training session) were likely to account for more variance in motion sickness susceptibility than many other, more time-consuming, costly, and invasive/intrusive approaches.

[17] These are optimal estimates of what the underlying correlation would be after correction for variations in measurement reliability.

[18] Large effect is ≥ 25% variance; medium effect is ≥ 9%.

[19] For example, the Brief Vestibular Disorientation Test devised by Ambler and Guedry [62] was one of the more promising and least time-consuming lab rotation tests for predicting airsickness (the sickening head movements lasted only ~5 mins). Five publications concerning this test are presented in Kennedy et al. [3] – they yielded observed correlations which can be described as medium on average (median 0.39, M 0.36 (SD 0.1).

[20] See the footnote 28 caveats concerning field dependence.

One of the most comprehensive meta-analysis that has been attempted since Kennedy et al was carried out recently by Mittelstaedt et al. [32], [63]. They screened 1,778 abstracts to identify 184 relevant publications, whose sample size ranged from 8 to 80,494, with a median of 50.[21] They found that many of the hypothesized relationships were based on limited, mixed, or controversial results. Their research looked at some of the same predictors as Kennedy et al., as well as many additional ones (such as age, sex, family history of motion sickness, state of motion habituation, or proclivity for migraines). It also contained more cybersickness studies. Some of the findings were quantitatively meta-analyzed. The findings are summarized in Table 5-3. The key inference we draw from the potential predictors assessed by Mittelstaedt et al. [32] is as follows:

1) Among the four variables for which specific estimates of effect size ranges or medians were feasible and communicated by Mittelstaedt et al. [32], the variable which appeared to yield the strongest (albeit not a large) median effect across multiple studies was field dependence, which yielded a 0.47 median effect, provided only rod-and-frame test findings were considered. This is in agreement with Kennedy et al. [3] who also found field dependence to be useful (with an observed predictor validity of 0.39).

In addition, we hypothesize that heritability appears to be an especially promising measure, but further studies are needed, and effect sizes were not specifically estimated.

Table 5-3 refers to further meta-analytic evidence concerning the performance of eight sickness predictors (adapted from Ref. [32]). The two most promising predictors studied were field dependence and heritability.

Table 5-3: Further Meta-Analytic Evidence Concerning the Performance of Eight Sickness Predictors.

Predictor Type	Importance of Predictor	Literature Basis (Quality of Evidence)	Possible Confounds or Caveats	Most Similar Predictor Category from Ref. [3]
Sex (female)	Different symptom severity: ratings: mean weighted effect size = .46 survey; .22 experiment	23/40 significant difference in symptom severity: 17/18 significant in history survey; 6/22 lab study (But only 4/14 studies where women had greater CIs not overlapping zero in Figure 2 of Ref. [32]).	There are numerous sex confounds and unconvincing findings in the literature (see Section 5.1.4.1.2 on sex in this report).	N.A.

[21] Note that the majority of the studies were motion sickness surveys, so this high median does not imply that most studies were large-sample empirical lab studies.

Predictor Type	Importance of Predictor	Literature Basis (Quality of Evidence)	Possible Confounds or Caveats	Most Similar Predictor Category from Ref. [3]
Heritability (family member susceptible)	~58% heritable [22]	6 studies mentioned (not counting ethnicity studies). "All studies indicated a genetic contribution" (p. 180 [32]).	Small number of studies. Confound of family experience (opportunities for habituation to boats, aircraft, etc.)	N.A.
Vestibulo-ocular reflex time constant (longer)	Range of effects by study: 0.20 – 0.59	6/11 studies	Confounds include age, habituation.	End Organ
Field Dependence	6/7 studies found significant correlation with rod and frame; 0/1 with a test similar to rod and frame; 0/4 with embedded figures, pooled correlation from five analyzable rod / frame studies = .47	6/12 obtaining significant finding	Many potential confounds, such as sex, age.	Psychological
Anxiety (higher)	"Most of" (p. 182) effect sizes ranged from $r = 0.26$ to $r = 0.41$	10/14 study effect sizes whose 95% CIs do not overlap 0	Confounds include aversive conditioning, vestibular maladies, sex, social desirability of reporting. Low variance accounted for in anxiety findings [3], and mixed findings [37].	Psychological
'Sympathetic Activity' (mixed)	Not summarized	3/5 found significant positive relationship of aerobic fitness vs. MS (implies low sympathetic tone), but 3/3 salivary studies found relationship (high tone)	Many potential confounds, including age, arousal level, experience. Inferences about tone rather than direct measurement in some studies.	Physiological

[22] 55 – 70% heritability is quoted by quoted in Ref. [64].

Predictor Type	Importance of Predictor	Literature Basis (Quality of Evidence)	Possible Confounds or Caveats	Most Similar Predictor Category from Ref. [3]
‘Sympathetic Activity’ (mixed) Cont’d			‘Autonomic response’ meta-analytic evidence not promising (Table 5-2).	
Habituation	Not summarized	~8 relevant studies mentioned; not quantified	Confounds include age (but 5/16 studies found increase MS; 4/16 found decrease) Insufficient quantification	N.A.
Migraine	Not summarized	14 relevant studies mentioned; not quantified	Confounds include vestibular maladies, sex, age Insufficient quantification	N.A.

We are aware of one more recent meta-analysis by Saredakis et al. [65], which looked at two specific user characteristics: sex and age (along with several non-user variables). They evaluated 1,609 unique articles of possible relevance to cybersickness. They screened the titles and abstracts of these articles to identify those using the SSQ to assess symptoms in HMD. They deemed 292 articles to be worthy of full-text screening. Through full-text screening and additional author contacts, they selected 55 relevant articles for analysis. These final articles comprised a total sample of 3,016 participants, whose pooled mean age was 24 (range 19.5 – 80), and among whom, 41% were female. Their meta-analysis did not find sex to be a significant correlate of sickness susceptibility. They found age to be a significant contributor to sickness susceptibility but pointed out that the data were too limited to draw firm conclusions. Their findings are summarized in Table 5-4.

Table 5-4 provides summaries of sex and age findings from Saredakis et al.’s meta-analysis [65].

Table 5-4: Summary of Sex and Age Meta-Analysis.

Predictor Type	Importance of Predictor	Literature Basis (Quality of Evidence)	Possible Confounds or Caveats
Sex (female)	A correlation was performed between the percentage of females in studies and total SSQ scores, as breakdowns for sex of means for the SSQ scores were not supplied in most studies. Bivariate correlations between the SSQ and percentage of females in studies failed to be significant ($r = -0.172$, $p = 0.170$).	51 studies had men and women participants (total n not stated).	Sex confounds are similar to those already described in Table 5-3. Also, the indirect percentage method the authors had to employ in this study was an acknowledged limitation. Finally, the authors observed high variation across the studies.
Age	Significant difference between young and old groups (non-overlapping 85% confidence intervals).	50 studies had subjects whose mean age was less than 35 (n not stated but ~2,952) [23], while 4 studies were located where the mean age was ≥ 35 ($n = 64$). The studies with the older subject lower SSQ scores than the studies with the younger subjects.	Confounds: Experience, sensory degradation, different display scenes, etc. Caveat: Only four studies in older subject group, so findings cannot be considered conclusive.

The meta-analysis findings of Kennedy et al. [3], Mittelstaedt et al. [32], and Saredakis et al. [65] are compared in Table 5-4. Our practical recommendations are listed below, based upon the collective trends observed. Our key conclusions are as follows:

1) Consensus Findings from the Three Meta-analyses:

   a) The three analyses studied ~12 candidate predictors overall, none of which was studied by all three.

   b) Among potential predictors studied by 2/3 analyses, the greatest agreement among the studies was the conclusion that field dependence probably is useful while autonomic response probably is not.

   c) Concerning sex, the variable studied by all three analyses, the findings were mixed.

2) Recommendations Based on Strongest Findings from Either Study:

   a) Past severity of symptoms appears to be a valuable and practical predictor of motion sickness. A motion sickness history survey is worthwhile, plus tracking of symptoms during initial exposures to the training or operational stimuli of interest. All other measures are optional.

   b) Field dependence may also be worth assessing in cases where time and equipment allow, especially when it is not possible to directly assess symptom response to a prior exposure to the stimulus of interest. The field dependence measure also plausibly be hypothesized to detect aspects of variance that would be different from those captured by past symptom severity estimates [3], which makes it of interest for research efforts.

[23] It is not clear whether 55 or 54 total studies were included (see p. 1 vs. p. 9 of Ref. [65]).

c) Family history of susceptibility should be assessed when feasible, in order to build up the database concerning this potentially important predictor.

d) Judgements concerning an individual's inherent resistance to experiencing severe symptoms during exposure to motion, simulation, or virtual environments could be confounded by that person's current state of habituation, anxiety, aversive condition, and other factors of which clinicians, trainers, or unit commanders should be aware when making decisions concerning readiness for training or duty, or treatment of sickness.

The following Table 5-5 shows the comparison of the most promising motion sickness predictors across three meta-analyses [3], [32], [65]. **Grey cells** indicate variables not assessed by a given meta-analysis. **Green cells** are variables deemed useful in at least two meta-analyses. **Red cells** are variables deemed **not** useful in at least two meta-analyses.

Table 5-5: Comparison of the Most Promising Motion Sickness Predictors Across Three Meta-Analyses.

Useful Predictor?	**Kennedy et al.** [3]	**Mittelstaedt et al.** [32]	**Saredakis et al.** [65]	**Current Recommendations**
Transportation Symptom Severity	Yes, #1-ranked.	Not assessed.	Not assessed.	Promising findings in a meta-analysis. If past response in same situation is known, this is valuable.
Lab Testing Symptom Severity	Yes, #2.	Not assessed.	Not assessed.	Promising findings in a meta-analysis. Valuable to know, but labor-intensive.
Retrospective History of Sickness Likelihood in Various Situations	Yes, #3.	Not assessed.	Not assessed.	Promising findings in a meta-analysis. Easy to assess and valuable.
Field Dependence	Yes, #4.	Yes, not ranked, but certainly in top three mentioned in terms of strength of findings.	Not assessed.	Moderately easy to assess and somewhat useful; emerged as a promising predictor in two meta-analyses. Caveat: requires special equipment.
Personality	No, generally weak.	Yes, anxiety somewhat useful.	Not assessed.	Mixed findings. May or may not predict motion sickness but important to assess in any study where arousal/anxiety state would be a confound (e.g., when using stimuli novel to participants, when sever sickness is likely, or when measuring drowsiness, many physiological correlates of sickness, or postural stability as a correlate).

Useful Predictor?	Kennedy et al. [3]	Mittelstaedt et al. [32]	Saredakis et al. [65]	Current Recommendations
'Autonomic Response'	No, generally weak.	Mixed findings and measures.	Not assessed.	Emerged as a less-useful predictor in two meta-analyses. Should be considered an exploratory variable in the research setting.
'End organ'	No, generally weak.	Vestibular time constant somewhat useful.	Not assessed.	Mixed findings. Exploratory; labor-intensive.
Heritability	Not assessed.	Yes, but not many studies.	Not assessed.	Easy to assess and possibly useful.
Sex	Not assessed.	Yes, but findings vary, and literature mixed.	No significant difference detected.	Mixed and weak findings. Easy to assess but only valuable when confirmed directly as a predictor in a controlled sickening study.
Habituation State	Deemed not enough data for meta-analysis; but ability to adapt was important in limited studies.	Yes, but few studies.	Not assessed.	Emerged as interesting in one meta-analysis. Important to know, perhaps during recruitment (to reduce confounds unrelated to treatment condition).
Migraine Susceptibility	Not assessed.	Yes, pooled effect unknown.	Not assessed.	Emerged as interesting in one meta-analysis. Easy to assess; exploratory.
Age	Not assessed.	Not assessed.	Significant difference but limited data.	Emerged as interesting in one meta-analysis. Easy to assess; exploratory.

5.1.6 Collective Consideration of Modelling Studies Relative to Meta-Analyses

While we located three meta-analyses, it is worth noting that there were three additional modelling reports of interest, wherein literature reviews were completed and variables from the literature (and the authors' own data) were incorporated into mathematical or statistical models to estimate the relative usefulness of candidate predictor variables [4], [26], [31], [36]. Below are the four main model variables that either agreed with the findings of the aforementioned meta-analyses, or were variables **not** included in the prior meta-analyses but deemed important enough to be featured in at least **two** of the three aforementioned modelling publications.[24]

1) History of motion sickness was deemed a useful predictor in one modelling report [4] and one meta-analysis [3].
2) History of migraine or headache was mentioned in one modelling report and one meta-analysis. While this was mentioned as a useful predictor in one meta-analysis [32] and deemed worthy of incorporating into the model by Rebenitsch and Owen [4], it was dropped from the latter because it **decreased** adjusted variance.

[24] A fifth variable mentioned in Ref. [34] (viz., experience with VR or dynamic video games) could prove interesting in future, as a similar variable was useful in a cybersickness history survey development effort [5].

3) Age was mentioned in two modelling reports [26], [36], and one meta-analysis [66], but there is a need for more data on older subjects.
   a) Kolaskinski [36] accounted for 35% of the variance using a model that incorporated age, sex, and mental rotation ability.
   b) Porcino et al. [26] found age a useful predictor of symptoms in various gaming scenarios. Specifically, it was useful for distinguishing 18 – 36-year-old subjects from two (very small) older groups (Table 5-3 [26]).
   c) Saredakis et al.'s [65] meta-analysis found age to be able to distinguish simulator sickness questionnaire total severity score between subjects younger than 35 vs. 35 and older, but identified only four relevant studies in their study which had a mean age >35 years (vs. 50 studies with younger mean age).
4) Sex was mentioned in two modelling reports and two meta-analyses, but the findings were mixed and weak.
   a) Weak Finding: This was mentioned in Kolaskinski [36] but their total model (with all variables) only accounted for 35% of variance and they did not detect sex as significant in a subsequent study [66].
   b) Contrary Finding: Sex was mentioned as a relevant variable in a modelling study [26], but there were relatively few women in the sample and the trend was for women to be less susceptible.
   c) Insufficient Data: Sex was deemed [4] to be a factor of interest in the past literature, but not incorporated into their final Demographic Cybersickness Model, because it was deemed not to have enough supporting data. Similarly, sex was mentioned [32] as a variable of potential interest, but not included in their final model due to insufficient data.
   d) Negative Finding: A significant sex difference was not detected in Saredakis et al. [65].

Based on the collective findings summarized above, it seems advisable to adopt motion sickness history questionnaires for sickness prediction in the military setting, and to consider further controlled laboratory studies on the role of individual age and history of headache/migraine. The literature findings are complex for age, and some of the more interesting findings (e.g., before the age of 18) lie outside the age range featured in the active-duty military. Findings are mixed for sex, and it cannot currently be described as a strong or proven predictor, but determining this is important, as women form a growing proportion of combatant personnel. Moreover, age, sex, and headache are each easy to assess and including them as covariates in future research studies would help to definitively determine whether they play a significant role in individual susceptibility.

5.2 TECHNOLOGICAL FACTORS IMPACTING CYBERSICKNESS

Most VR goggles are making use of an integrated display and an optical system to display visuals to the human eye that are rendered in conjunction with sensor based spatial tracking solutions at high frame rates. VR goggles can realize mono or stereoscopic perception of a synthetic and immersive scenery. From an engineering standpoint, these wearable devices can be divided into several parts directly or indirectly affecting cyber sickness. The quality and accuracy of the motion-to-photon pipeline (Figure 5-2) are key contributors to the virtual reality experience and involve latency between the user's motion and the respective update of the display content (motion-to-photon latency), jitter (random shaking of the content) or drifting to display resolution and spatial based audio correlated to content and scenery. The technological factors directly or indirectly affecting cybersickness can be divided into:

- Optical related factors;
- Display related factors;
- Spatial tracking related factors;

- Audio related factors; and
- Form factor related factors.

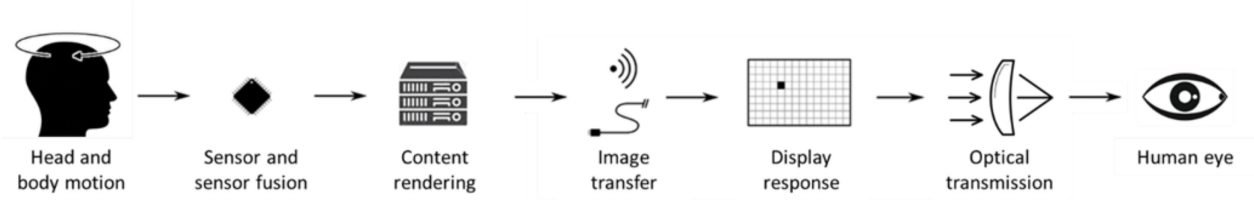

Figure 5-2: Motion-To-Photon Pipeline.

5.2.1 Optical Related Factors

The main optical related factors identified for Commercial-Off-The-Shelf (COTS) HMD with effect on cyber sickness are:

- Binocular viewing and inter-pupillary distance;
- Field of view;
- Focal distance and image plane; and
- Optical aberrations.

5.2.1.1 Binocular Viewing and Inter-Pupillary Distance

Binocular viewing refers to each eye having an individual viewport. In the case of virtual reality, two camera points, one for each eye, are rendered and passed to the HMD. While binocular viewing greatly increases presence and realism, it can also induce nausea and cybersickness and is especially common when the Interpupillary Distance (IPD) is not set appropriately which leads to convergence accommodation conflicts [67], [68]. Interpupillary distance is a foremost concern when using stereoscopic and immersive display technologies and is the measured distance between a subject's pupils. One recent study [68] found IPD mismatch to be the principal cause of cybersickness. The optics and displays should be carefully calibrated to match the viewer's IPD. The Interocular Distance (IOD) is defined as the measured distance between the two optical centers of a stereoscopic displays. Those with IPD less or more than the IOD, experience increased visual discomfort and increasing symptoms as the mismatch increases [68].

The quality of the stereo vision is contingent on the correct alignment of the lenses IOD of the HMD with the IOD of the user. In humans, the average adult IPD is 63 mm, with the majority of adults having IPDs between 50 mm and 75 mm [69]. Misalignment leads to decreased quality stereo vision, diffuses the rendered image, and can result in cyber sickness or headache. Considering the deployment of the HMDs across a broad range of the population, it is critical that modern HMD systems become equipped with variable IPD [70], [71].

5.2.1.2 Field of View

Field of View (FoV) describes the extent of the VE that is visible through the HMD, i.e., the angle of view from the user's eye to the lens. Higher FoV is associated with higher immersion as the user is able to perceive more of the virtual world [72], [73]. This measure is not constant for HMDs allowing users to change the distance between the eye and lens.

While precise figures are the subject of debate, a human eye has a field of view of roughly 160 degrees vertically and 180 degrees horizontally [74]. To mimic human vision, an ideal immersive display technology would have a field of view, which meets or exceeds that of human vision. Due to cost, ergonomic, and computing limitations, most HMD stereoscopic displays have a considerably smaller field of view. Typical present-day virtual reality headsets, for example, have a field of view roughly half that of human vision. For mainstream augmented reality headsets, the situation is more direct where a typical field of view is 10 to 25 percent of that of human vision. Increasing the field of view is generally associated with increased cybersickness. However, some studies using modern VR headset do not indicate as strong of a correlation with increased cybersickness and increased FoV [75].

In addition to the FoV of the display, the FoV of the virtual camera should also be considered. A virtual camera FoV can be set independently of the HMD FoV [76]. When the FoV of the camera is less than that of the HMD, a zooming in effect is achieved; likewise, a larger camera FoV is akin to zooming out. Field of view can also be restricted by masking the image on the display itself. A reduction in the FoV is associated with decreased immersion creating a potential trade-off between FoV and cybersickness [76]. Another study, however, found most sickness when both types of FoV were made equal [77].

5.2.1.3 Focal Distance and Image Plane

At the time of writing, all consumer grade VR headset have a fixed focal distance. A common cause of visual discomfort using stereo vision devices can be eyewear with separation between eyes, incorrect calibration or poor focus simulation, and convergence accommodation conflict [76]. Difficulty focusing can be a contributor to cybersickness [78], [79]. Depth information in stereoscopic information is extracted from the state of the eyes via depth cues [80], [81]. Some depth cues are physiological (accommodation, convergence) or psychological (overlap, object properties, motion, parallax, linear perspective, texture gradient, height in the visual field). The sum total of these cues form depth information and one must be cautious to provide contradictory cues [81]. Human vision is three-dimensional and relies on depth cues like eye convergence and stereopsis based on retinal disparity which may greatly increase immersion [81], see also Chapter 2.

5.2.1.4 Optical Aberrations

Aberration is a property of optical systems that causes light to be spread out over a region of space instead of being concentrated on a point, causing an image to be blurred or distorted. Aberrations are always present in a lens. Aberrations are of concerned, especially in low-cost optical consumer products (compared to more expensive solutions) where less care has been taken to purity in glass material and combinations of materials and geometric form in comparison to more costly designs. How aberration in COTS HMD optics affect cyber sickness is a complex question and depends on how the images are rendered and visualized by the display.

Spherical aberration causes different parts of an image to be focused on different points, meaning if you want the center of your image sharp and clear, the edges will become progressively blurry. Chromatic aberration occurs when different wavelengths are not focused on the same point. There is also a barrel and pincushion distortion, which are often found when lenses try to correct for the above two distortions, and when trying to produce a wide field of view. These cause the final image of, say, a straight grid of lines to be either stretched (barrel distortion) or pinched (pincushion distortion), see Figure 5-3 below. Image distortions and other artefacts can partly be corrected for in software and in the imaging rendering pipeline.

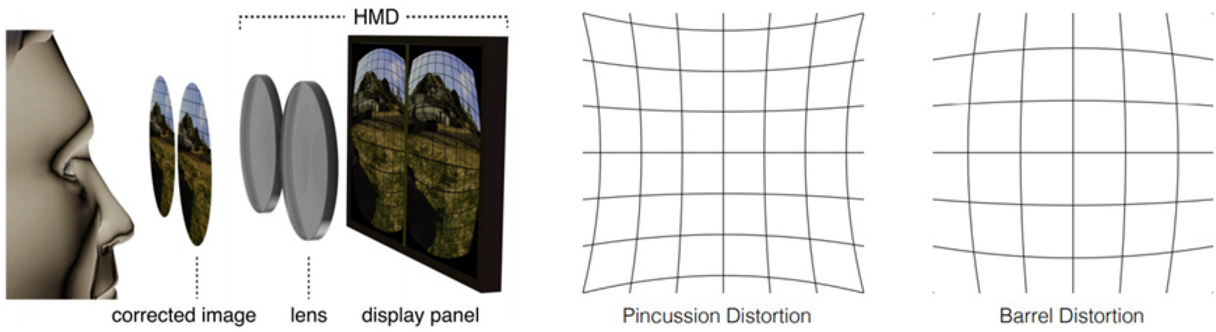

Figure 5-3: Image Aberrations.

5.2.2 Display Related Factors

There are many types of display solutions for VR goggles. From commercial off-the-shelf products to novel and innovative work in applied and fundamental research. Some of which are varifocal displays [82], [83], handling the negative effects from vergence accommodation, multiplane displays [84], [85], with addressable focus planes and large flicker impact, light field displays [86], tensor displays [87], vision-correcting display [88], Maxwellian-type displays [89], etc. Display related factors for most current commercially available VR goggles:

- Display resolution;
- Time lag (transport delay);
- Screen flicker;
- Display pixel lag; and
- Refresh, update, frame rate and motion blur.

5.2.2.1 Display Resolution

Display resolution is a measure of the number of pixels composing the display. Higher resolution correlates directly with the quality of the visual perception, immersion, and the level of detail.

Resolution is regarded as one of the most important characteristics of a micro display and an important factor to maintain immersion. Since most current display technologies use a grid of pixels, angular resolutions must be translated accordingly. Pixels per inch (ppi) is the common nomenclature used to express pixel density. A human's ability to resolve pixels depends on the distance from the eye to the display. Most currently available mainstream consumer VR headsets offer a pixel density in the 400 – 600 ppi range [90]. As display technology evolves and computing power increases, commensurate increases in pixel density are expected.

A powerful technique is to maintain high resolution in the foveated region of the eye [91], which also saves computer rendering power and data bandwidth requirements. This can be accomplished by rendering images with the technique called foveated rendering, where an image is split into n layers, e.g., inner (foveal, 1), middle (2), outer (3) etc. that renders an image in each zone with progressively lower resolution [92].

5.2.2.2 Time Lag (Transport Delay)

Time lag refers to the delay caused by processing inputs and then producing and displaying an image associated with those inputs [79]. However, Virtual reality headset makers continually seek to reduce transport delay. Especially in VR scenarios, care should be taken to reduce transport delay whenever possible. One source says that a time delay exceeding 50 ms between head movement and display response can cause sickness in VR [93].

Displays have varying image processing times which can be a chief drive of transport delay. Gaming monitors, for example, are specifically crafted to reduce image processing time and, thus, transport delay. Displays targeted to professional artists often have considerable post-processing to produce higher fidelity imagery, resulting in a typically much greater transport delay. Gaming modes that are common in consumer televisions sacrifice perceived image quality to reduce image processing time.

5.2.2.3 Screen Flicker

Flicker is an artefact, sometimes induced by the display but often controllable in the construction of the virtual environment that can cause cybersickness symptoms of both nausea and eyestrain [79]. Flicker above 30 Hz is generally not detected in central vision but may be detected in peripheral vision [79]. The threshold at which flicker becomes perceptible is termed the flicker fusion frequency threshold. The threshold changes with the circadian rhythm (day and night) [94]. Individuals exhibit a spectrum of flicker fusion frequency thresholds. Increased display brightness causes increased flicker [79].

5.2.2.4 Display Pixel Lag

Display pixel lag can be defined as time elapsed between when a command is sent to a pixel and the response to that command. Lags in the visual display can be a cause of cue conflict. Time lag from transport delay, the time period from input to the completion of the first field of video output, could potentially affect both performance and cybersickness symptoms [79]. Mostly, pixel lag is a concern in displays utilizing Liquid Crystal Display (LCD) technologies. Digital light projection, a common projection display technology has excellent pixel response time [95].

5.2.2.5 Refresh Rate and Update Rate

A display’s refresh rate refers to how often the image is updated and is measured in Hertz (Hz). Higher refresh rates are associated with higher display fidelity. Refresh rate is related to the problem of flicker and slower refresh rates promotes flicker that can cause cybersickness symptoms of both nausea and eyestrain [79].

5.2.2.6 Frame Rate and Jitter

Each image produced by a simulation is referred to as a frame. Each frame takes a discrete amount of time to process and display. Frame rate refers to the number of frames the simulation produces over an average time. Frames per second is the often-used metric. All else being equal, higher frame rates are desirable in a simulation to increase visual fidelity, realism, and immersion [96]. However, to derive a frame rate, the number of frames displayed must be averaged over some amount of time. Thus, a simulation may have an average frame rate of 120 Hz (8.33 ms per frame) but only have a subset of the frames rendered in less than 8.33 ms. Jitter refers to the variability in interframe rendering time. Frames that take longer to render are negatively and abruptly perceived by the user as stutters that may induces headaches and nausea [79], [96]. Thus, it is desirable to have a frame rate whereby a high percentage of the frame are rendered in less time than the refresh rate. As a general rule of thumb, at least 95% of the frames should be rendered within the time of a monitor refresh. If the simulation is particularly demanding and has rapidly changing imagery and viewpoint, a higher threshold such as 99% can be targeted. Research results suggest that low jitter and high frame rate are important for presence [97].

5.2.3 Spatial Tracking Related Factors

5.2.3.1 Tracking Systems and Spatial Degrees of Freedom

Many types of COTS HMD contain a tracking system which maps the wearer's movements and adjusts the images accordingly. Each time the wearer moves his head, walks in a particular direction, or takes some other form of action, the scene changes accordingly. The tracking system is connected to a computer, which adjusts these images so that the wearer is shown a realistic environment with a realistic depth of perception. There are in general two types of tracking:

- Inside-out tracking: camera or sensor is located on the HMD, no need for other external devices to do tracking; and
- Outside-in tracking: external sensors, cameras, or markers are required (i.e., tracking constrained to specific area).

Outside-in tracking have been used by most VR headsets in the past but to reduce the need of external equipment's, set-up time and calibration, insight-out tracking solutions are eventually required by all untethered HMD systems. Outside-in tracking solutions are commonly based on either or a combination of:

- Mechanical tracking;
- Ultra-sonic tracking;
- Magnetic tracking;
- Optical tracking;
- GPS;
- WIFI positioning; and
- Marker based tracking.

A tracking system allowing for six Degrees Of Freedom (DOF) is necessary for most applications and in particularly to allow for near real-world experience in virtual sceneries.

5.2.3.2 Position Tracking Errors and Noise Influence

For immersive displays, precise tracking of the user's position and orientation is necessary to provide a convincing experience. Tracking technologies vary in their implementation (inside-out vs outside-in) and fidelity. In the often-cited case of consumer VR headsets, poor placement, or obstruction of line of sight can lead to poor tracking quality. Similarly, interference, depending upon the technology employed can cause issues with the quality and precision of the tracking. When there is a mismatch between the measured position and orientation value and the actual value, jitter occurs. Jitter has been shown to cause cybersickness [96]. Jitter is not limited to the tracking head position and orientation but can also manifest in other tracked objects, such as controllers, and cause cybersickness. Position tracking is the key means for adequately coupling the user's head, vision, and sometimes hands or body, to the virtual environment. Errors in position tracking can lead to visual-proprioceptive conflicts [79] and if tracking is lost, disturbing oscillations in the 0.2 to 0.25 Hz range may be exacerbated [79].

5.2.4 Audio Related Factors

An integrated audio system eliminates the effort for mounting a peripheral audio device such as headphones. External headphones require additional cables and can interfere with the ergonomic head-strap if they do not optimally fit-on the HMD, user comfort can be significantly decreased. Integrated audio technologies are further sub-categorized to:

1) Earpieces that block substantial amount of background sound; and
2) Open sound systems that do not block any real-world sounds.

Currently there is not enough research present to fully characterize the benefits and drawbacks of different audio technologies in VR devices and in particular those affecting cyber sickness in terms of audio perception based on mono, stereo, 3D / spatial audio with Head-Related Transfer Function (HRTF) and Anatomical Transfer Function (ATF).

5.3 OPERATIONAL FACTORS IMPACTING CYBERSICKNESS

The intent of this section is to describe how the severity of cybersickness may be impacted by various operational factors. We define operational factors as actions of the individual in the environment (method of control, degree of control, head movements), conditions imposed by the environment (e.g., optic flow motion and features) and scenarios or specific use cases (e.g., duration spent in virtual environment). We examined the literature on cybersickness during these operational conditions to derive recommendations on how to reduce it.

5.3.1 Degree of Control

A factor that has been associated with the occurrence and severity of cybersickness is the degree of control an individual has over their movements in Virtual Environments (VE). Passengers in a road vehicle often get sicker than the driver [98]. Rolnick and Lubow [98]. exposed pairs of participants to the same rotational accelerations where one of the participants controlled the motion platform. The passive participant experienced significantly more sickness and reported decreased well-being compared to the participant controlling the movement. Similar findings have been reported in multiple studies [99], [100]. Interestingly, it has been shown that this effect could be replicated in a fixed-base, visual-only driving simulator. Researchers [101] let participants actively steer a vehicle in a virtual environment and made a video recording of each participant's run. Subsequently, these recordings were shown to a different set of participants, effectively making them passengers in the virtual vehicle. In this passive viewing condition, 69.2% reported feeling sick, while only 15.4% of the active drivers did. Symptoms were also significantly more severe for the passive individuals as measured by the SSQ. Summarizing the abovementioned findings, an operational factor that most certainly will affect the occurrence of cybersickness is the degree of control over self-motion an individual has while in the VE. This holds true regardless of the presence of physical motion.

5.3.1.1 Method of Control

Method of control refers to the means through which an individual controls their movements in the virtual environment. Examples include use of a steering wheel, buttons on a keyboard, or a joystick to guide a vehicle. Research has been conducted on the influence of the method used to move within a VE on various forms of motion sickness including cybersickness. A recent study [102] compared joystick and bike ergometer guided control of a virtual bicycle impact on cybersickness. In the bike ergometer condition, the participants controlled their motion as they would when riding a real bicycle; by increasing pedal input, rotating the handlebar, and braking with a hand brake. The study, however, did not find a difference between the two conditions on SSQ scores. To our knowledge, no research has been performed on impact of input device on cybersickness in military-relevant tasks.

5.3.1.2 Method of Movement

Studies have investigated how different methods of movement of the individual within a virtual environment influence the occurrence of cybersickness. Common methods of locomotion in the virtual environment include naturalistic free movement about the VE such as walking, teleportation throughout the VE and node-based locomotion. Naturalistic free movement has been found to induce greater cybersickness than teleportation [103], [104], [105]. Teleportation reduces sensory conflict generated from optic flow input by completely skipping the visual transition period between two points. One study's findings contradicted this general trend in some participants, highlighting the strong inter-individual differences in cybersickness [106]. A significant drawback of using teleportation for movement is the potentially strong negative influence on performance and possibility of directly interfering with the training objective or main task [103]. Farmani and Teather [107] successfully employed a technique they call viewpoint snapping to combat severity and onset of cybersickness during stationary, vertical yaw rotations. The technique involves rendering the moving imagery in discrete chunks, skipping the individual frames that would usually be shown during a rotation. This reduced optic flow and associated visual-vestibular conflict. They found a significant reduction in SSQ scores using viewpoint snapping compared to non-snapped rotations. However, the authors note that even though the technique can be used effectively to counter the occurrence of cybersickness, it was found by some participants to be disorienting initially and interfered with the primary task. Another study [108] looked into the effects of three different methods of movement in a virtual environment on cybersickness and usability: teleportation, continuous free locomotion and rapid, continuous node-based locomotion. Node-based locomotion is a technique where the user can access only pre-set nodes and movement is only possible to a neighboring node, which happens quickly compared to what is considered normal walking speed. Thus, this technique is similar to Farmani and Teather's viewpoint snapping technique in that it seeks to reduce optic flow and keep visual transitions as brief as possible. It is noted by the authors that even though the perceived motion is brief, it is strong and might therefore provoke sickness. Their analysis revealed that the node-based locomotion induced significantly lower SSQ scores in participants than continuous free locomotion. Node-based locomotion yielded similar SSQ scores to the teleportation condition, while also being perceived as easier to use than teleportation. Node-based locomotion did not affect task performance negatively, which would be a major concern when employing techniques in a training environment. Nonetheless, this might be highly task-specific and could play out differently for other more complex applications. Taken together, employing this kind of node-based motion and viewpoint snapping for stationary rotations could significantly reduce motion sickness as compared to naturalistic continuous free movement, while possibly circumventing performance degradation associated with pure teleportation but should be validated in military-relevant scenarios.

5.3.2 Head Movements

The current section explores how temporal frequency of motion of the visual scene and the head contribute to cybersickness. There is a vast literature on physical motion frequencies and their impact on motion sickness and performance (see for a review [109]). Moreover, the visual, vestibular and proprioceptive systems are thought to have differing optimal temporal frequencies for perceiving self-motion stimuli [110], [111], [112]. When stimuli are presented in frequencies that are sub-optimal for perception of self-motion for that sensory system, motion sickness may occur [113], [114]. In the current section, we addressed visually implied temporal frequencies of motion as well as some of the literature on inertial or vestibular frequencies as it pertains to cybersickness to identify visual or vestibular frequencies that provoke severe cybersickness, and how to avoid these.

5.3.2.1 What Simulated and Real Head Movement Frequencies are Most Likely to Induce Cybersickness?

Duh et al. posit that neither the visual, nor the vestibular systems optimally perceive sensory stimulation at 0.06 Hz [113]. They predicted that as a result of this, a conflicting visual-vestibular motion cue at 0.06 Hz should induce strong sickness. They tested this with a virtual optokinetic drum in a VR head-mounted display while rotating the participants in a chair in opposite (conflicting) directions. They rotated participants at frequencies of 0.2 Hz and 0.06 Hz and measured sickness with the SSQ. They found SSQ scores to be higher in the 0.06 Hz condition than in the 0.20 Hz condition as predicted. Groen and Bos used a motion-base driving simulator coupled with a projection system to investigate vestibular and visual motion mismatch frequencies when driving [115]. They found that mismatch frequencies between the visual and vestibular stimuli near 0.07 Hz provoked the most severe sickness in the visual and vestibular systems, supporting findings by Duh et al.

Diels and Howarth looked at visual for-aft frequencies impact on cybersickness at various frequencies and found that 0.2 – 0.4 Hz created peak sickness among the many tested using SSQ and the standard sickness scale [116]. This goes against Duh and colleagues' cross-over hypothesis [113]. However, cross-over hypothesis was examined in rotational conditions, whereas Diels and Howarth [116] examined frequencies in linear axes. Thus, visual frequencies provoking cybersickness may differ based on the axis of motion/sensory organ sensing motion (e.g., saccules and utricles or semi-circular canals).

Chen et al. manipulated frequency of a visual stimulus in the for-aft axis in two experiments by manipulating amplitude and velocity of the visual stimulus [109]. Frequencies they tested varied between 0.0125 – 3.2 Hz. Stimuli were projected on a cave like projector and a Likert scale was used to rate participants' level of nausea at 2-min intervals during the 30-min experiment. They administered the SSQ at the beginning and end of the experiment. Results of E1 indicate that there may be an interaction between amplitude and velocity of the display and that frequency is mediated by these. In E1, manipulations of frequency created significantly higher cybersickness scores when amplitude was held constant than when speed and frequency were held constant. This suggests that amplitude is more important than velocity and frequency for making people sick. In E2, they found a main effect between 0 Hz frequency and all others for nausea and SSQ scores. The frequencies authors tested appear to produce stronger cybersickness than 0 Hz frequency, but they did not find a particular frequency that provoked the most cybersickness.

Laboissiere and colleagues used a display that rotated in front of the participant with black dots on a white background at 30˚/s. The SSQ and MSSQ were used to measure sickness [114]. They conducted two experiments looking at visual and vestibular frequencies that induce sickness and hypothesized that participants whose natural sway, based on measures from a static posturography test, is 0.2 Hz would experience the most sickness because this frequency provokes severe sickness [116]. They found that their results supported this hypothesis. This is consistent with results reported by Diels and Howarth [116]. Thus, Laboissiere et al. found evidence that sway was the cause of sickness and not necessarily the predictor of sickness as postural instability theory posits [117].

There are many factors to consider when discussing motion frequencies of the head and visual display that cause cybersickness including the motion trajectories of the display, whether the visual display is moving or the head is moving, amplitude and velocities of the displays, and natural average sway of the individual. Bearing these factors in mind, there seems to be some agreement in the literature that the 0.06 Hz frequency may provoke cybersickness in the visual and vestibular systems in the angular and linear axes of motion. Diels and Howarth demonstrated that in the for-aft axis of motion, 0.2 – 0.4 Hz is the most provocative stimulus to induce cybersickness [116]. Though there are many questions left open on the topic of simulated motion frequencies that induce sickness, our recommendations regarding head movement and visual display frequencies that produce the most cybersickness and should thus be avoided appear to be within the 0.06 – 0.07 Hz range in the angular axis, and 0.06 – 0.07 Hz and 0.2 – 0.4 Hz in the linear axis of motion.

5.3.2.2 The Impact of Coriolis Cross-Coupling on Cybersickness

An example of Coriolis cross-coupling is when an individual's body and head are aligned and rotating relative to the earth vertical axis, then suddenly the head tilts in the roll axis. This gives a rotational angular impulse vector that is not aligned with the gravity vector in the head-centered reference frame and can cause severe motion sickness [118], [119], [120]. Situations where Coriolis-cross-coupling occurs include aerobatic flight or centrifuge training over prolonged periods [121], [122]. Coriolis cross-coupling can occur while wearing VR or AR HMDs but to our knowledge, there is no research that has looked at the interaction between HMD and Coriolis cross-coupling simultaneously. We predict that sickness resulting from Coriolis cross-coupling when wearing an HMD would largely depend on the HMD being appropriately set.

5.3.3 Global Visual Flow

Optic flow patterns simulate self-motion when walking, running, or operating a vehicle [123]. Virtual environment designers often use radial expansion of objects from the center of the display outward. to produce a convincing sense of illusory self-motion called 'vection' [124]. Generally, when we walk, run, bike, drive or pilot an aircraft, the visual world does not expand radially smoothly. There are bumps on the road, and heel strikes from bipedal walking/running and turbulence in an aircraft that result in perturbed visual optic flow patterns that occur. Researchers and VE designers simulate these perturbations to enhance realism in a graphic display.

This section investigates how different optic flow trajectories such as smooth radial motion, perturbed optic flow signaling forward self-motion and others impact cybersickness. The objective was to identify if there are some global visual flow patterns that can make a visual display more or less provocative for cybersickness. This information was used to predict and inform VE development for military training in determining which optic flow directions can provoke the most sickness and how to avoid these.

Keshavarz et al., investigated the impact of axis of motion combinations on cybersickness reports and vection in stationary individuals [125]. Researchers compared smooth linear motion to linear motion with added continuous yaw, pitch or roll axis motion presented on a screen. They found that participants were significantly sicker when yaw or pitch axes of motion were added to smooth radial motion using the Fast Motion Sickness (FMS) scale and the SSQ. These findings suggest that two simultaneous axes of motion generally produce more sickness than only linear axis motion. They also found that vection scores were greater with two axes of motion than one, though they did not report a significant correlation between vection and sickness severity (information on the relationship between vection and cybersickness can be found in Section 5.3.8 below). Results replicate earlier findings by this group using a roller coaster stimulus [126]. In this earlier experiment, Keshavarz and colleagues compared motion on a roller coaster in two axes (pitch and roll) of motion compared to motion on a roller coaster in three axes (pitch, roll and yaw) and found that higher cybersickness scores were reported in three axes than two [126]. They also stated that vection and cybersickness increased together but no correlation was reported. Other researchers have also found stronger vection with additional axis of motion combinations [127], [128]. In all findings so far indicate that three axes of motion produce more severe sickness than two, and that two axes of motion produce more sickness than one.

Gavgani et al. examined direction of motion on cybersickness using the FMS and the Motion Sickness Susceptibility Questionnaire (MSSQ) using an Oculus DK1 VR HMD [129]. They had a forward motion condition and a backward motion condition. Participants experienced more severe cybersickness in the forward motion condition than in the backward motion condition, consistent with findings by Bubka, Bonato and Palmisano [130]. In sensory conflict theory terms, these results may be explained by the fact that we experience moving forward more often than moving backward. Therefore, we have a more specialized sensory store for forward than backward motion that is more likely to conflict with our experience of moving forward, causing higher likelihood of sickness during forward than backward simulated self-motion in VEs [131].

Most studies with the exception of two by Diels and Howarth show that cybersickness severity increases with the number of axes of motion [132], [133], [134]. These findings hold important implications for military simulation and training applications. First, optic flow indicating forward self-motion produces stronger cybersickness than optic flow indication backward self-motion [129]. This is problematic for military use cases as forward self-motion is common. Second, the literature indicates that multi-axis optic flow trajectories produce more severe cybersickness than single axis optic flow. This again is problematic for military use cases as realistic self-motion usually requires multi-axis optic flow such as in walking or driving where forward motion is also accompanied by random perturbations in multiple axes. Thus, it appears that the use of optic flow trajectories most likely to be used for military training are those most likely to produce the most cybersickness. However, VE designers should limit multi-axis motion unless it is critical for the simulation

5.3.4 Rate of Linear and Rotational Acceleration

Recent research by Reinhard et al. examined the relationship between VIMS and reaction time [135]. The task required participants to drive in a fixed-base driving simulator and brake on command, prompting visually implied deceleration in a fixed-base simulator while reaction times and FMS scores were recorded. They found that FMS scores were higher and reaction time for braking was longer as the study went on. The results importantly demonstrated that sudden braking, causing rapid deceleration causes severe cybersickness. By sensory conflict theory accounts, these findings are consistent with the notion that greater conflict between visual and vestibular cues leads to stronger sickness. Other studies have also found that accelerating/decelerating displays cause stronger sickness than a display with constant velocity motion [132], [136], [137], [138]. In all, accelerations/decelerations in the angular and linear axes cause more severe cybersickness than constant velocity motions. Thus, we discourage the use of implied acceleration in optic flow to mitigate cybersickness.

5.3.5 Self-Movement Speed

It was concluded from findings presented in Section 5.3.4 that constant velocity motion in VR HMD produces less severe cybersickness than accelerating optic flow displays. But is there a specific speed threshold that produces stronger cybersickness than others? So, Lo and Ho investigated this question [138]. Though they found that time spent in the VR HMD was the most important predictor of sickness, they found significant differences in sickness as for-aft optic flow speeds increased. Specifically, they noted a sharp increase in SSQ scores between the 10 m/s condition and lower speeds, no significant difference between 10 – 30 m/s then another sharp increase in SSQ scores from 30 m/s to 60 m/s conditions. It is important to note however, that speed perception and thus, SSQ scores, are tied to optic flow elements that move past the observer, which is governed by the contrast of the display [139]. Owens et al., demonstrated this by showing that reduced contrast of the elements in the optic flow pattern by using fog in their study resulted in self-motion speed under-estimations by participants. Hu et al., found that faster optokinetic drum speeds resulted in increased sickness [140].

Similar findings replicating the positive association between optic flow display speed and increased sickness have been found by other researchers as well [141], [142], [143]. An experiment by Kwok and colleagues investigated the difference in optic flow speed in a VR HMD. Results indicated that participants experienced more severe cybersickness at 24 m/s than 10 m/s, but it is not clear from their report if order effects may have contributed to these findings [143]. These findings approximate those by So et al. On the other hand, Keshavarz et al. looked at display speed, and element density on vection and cybersickness [125]. Contrary to findings in Keshavarz et al. [138], detected no significant difference of display speed on sickness scores when comparing display speeds set at 15 m/s to 75 m/s. However, Keshavarz et al. found generally low SSQ and FMS scores throughout all conditions. Most research agrees that faster speeds result in stronger sickness [141], [142], [143]. Thus, unless fast motion speeds are needed for training scenarios, we recommend the use of slow optic flow speeds to reduce cybersickness.

5.3.6 Visual Scene Density and Altitude Above Terrain

Low level flight and land vehicle navigation naturally produce more complex visual patterns than high altitude flight. Kennedy et al. found stronger simulator sickness during low level flight than high altitude flight [144]. However, altitude above terrain is mediated by more basic elements of the visual scene. For instance, low level flight and land vehicle navigation produce high density optic flow with more visible elements in the visual scene at higher contrasts. The visual environment during high-level flight generally produces fewer visual cues, less densely packed visual elements and less contrast and is generally less reliant on unaided visual cues than low level flight. Contrast on its own does not appear to impact cybersickness [145], [146]. On the other hand, self-motion speed [138], [140], [141], [142], [143], temporal frequency and acceleration affect cybersickness [132], [135], [136], [137], [138]. Altitude above the terrain's impact on self-motion perception and cybersickness depends on contrast, self-movement speed, acceleration, and scene density. However, scene density may be a factor that impacts cybersickness and is therefore explored below.

Scene density is considered separately from speed, acceleration, and contrast. Density here is defined as the number of visible elements in the optic flow scene. It is reasonable to assume that high density scenes provide stronger cues to self-motion. Here we look at studies investigating scene density to understand its impact on altitude above terrain and its impact on cybersickness.

Keshavarz et al. looked at the impact of object density on cybersickness [125]. The optic flow display simulated forward self-motion by having dots expand radially from the center to the extremities of the display in a low-density condition and high density condition. Density was manipulated by changing the number of dots in the scene while speed of expansion of the dots was held constant. They failed to find a difference in SSQ and FMS scores between the low and high density conditions but found more intense and longer vection scores for the high density condition than the low-density condition. Their study showed floor effects for cybersickness, potentially causing no difference in sickness scores across conditions. To our knowledge, few studies have explicitly examined the impact of scene density on cybersickness. Lubeck et al. investigated scene density on vection, finding that increased density resulted in stronger vection, but they did not examine cybersickness in their study [147].

Increased density can produce stronger vection, but there is no evidence we are aware of directly linking increased scene density with cybersickness. Instead, density seems to impact vection and speed perception. Contrast also does not appear to directly impact cybersickness. Thus, there is no evidence supporting the notion that altitude above terrain directly impacts cybersickness. However, there is evidence suggesting some elements contributing to percepts of degree of altitude above terrain impact cybersickness (e.g., speed, acceleration) whereas others do not (e.g., density and contrast). We therefore recommend that elements that contribute to increased scene density be considered separately rather than altitude, or other viewing conditions on their own when discussing their impact on cybersickness as altitude above terrain does not directly impact cybersickness.

5.3.7 Luminance Level

Shahal et al. examined the impact of contrast and brightness of a visual scene presented as mountainous terrain from a passively flown fixed-base aircraft simulator, consisting of 3 desktop monitors presenting the moving scene [146]. Researchers varied brightness and contrast in their experiment by presenting a clear daytime flight condition, a night-time condition, a fog condition, and an aided night-time condition. They found no difference in FMS scores across these four conditions compared to baseline. Dziuda et al. also did not find contrast manipulations to significantly impact cybersickness when measured with the SSQ [145] Owens et al. manipulated contrast and found that participants' self and object rates of motion percept were slower when contrast reducing manipulations such as fog were used, however they did not measure cybersickness [139]. We found few studies examining the impact of luminance and contrast on cybersickness. Among the two studies found on the topic, both did not report significant differences as a result of contrast and brightness manipulations. However, luminance may impact cybersickness indirectly. For instance, studies have shown that increased contrast can impact speed perception [139]. Related to this finding, other studies have shown that increased speed perception increases vection and cybersickness [140], [141], [142], [143]. Thus, contrast may not be a factor that directly impacts cybersickness, but it may be related to other factors such as self/stimulus velocity.

5.3.8 Vection

Vection[25] refers to the illusion of self-motion that is readily elicited (usually visually) by any moving stimulus that is perceptually interpreted as a stationary reference point (e.g., an adjacent car rolling forward at a stoplight) or an ambient frame of reference (e.g., a rotating ambient visual surround). In a VR, such an illusion can be exploited for simulation and training purposes as an easy and inexpensive way to simulate body motion. However, moving visual fields also can elicit VIMS. Hettinger et al., posited a possible relation between the vection illusion and VIMS, based upon an interesting preliminary finding (a nonsignificant correlation) [148]. In 2005, Lawson employed a slowly-rotating immersive visual surround stimulus intended to elicit maximum vection with minimal VIMS [149]. This study demonstrated very strong vection in all 45 subjects, without nausea being reported by any participants. This conclusion is promising for VR dissemination and has recently been corroborated by Kuiper, Bos, and Diels [150]. Moreover, Ji et al. [151] reported the opposite case, wherein VIMS was obtained without eliciting vection, which had been observed also by others [151].

While the findings above indicate that vection is not necessary or sufficient for VIMS, the two variables may be related. Does the literature confirm this possibility? Lawson [152] identified 10 relevant MS studies in the literature which offered any relevant evidence concerning the possibility that vection and VIMS are related. Lawson found that only 3/10 (30%) of the studies provided compelling evidence of a significant relation between vection and VIMS, and the relation was usually only seen in the largest sample studies (suggesting a limited effect size). The current literature evidence appears insufficient to permit the assertion that there is a strong and significant positive correlation between vection and VIMS. Therefore, limiting vection is not a recommended constraint to VR simulation or preferred countermeasure for cybersickness. However, limiting stimulus factors such as the speed of visual flow could be helpful.

5.3.9 Duration

The current section aims to determine the amount of time necessary to experience cybersickness and the amount of time required to recover from cybersickness. These findings were used to make informed decisions about the amount of time that users can be in VR HMDs for military training applications.

5.3.9.1 Duration of Exposure to Cybersickness-Inducing Stimuli

Many studies on cybersickness using simulators and VR HMDs have noted that the length of time of exposure to a virtual environment increases severity of sickness [136], [153], [154], [155]. Increased sickness with time spent in VR HMDs is a critical problem for military training because long durations of training are to be expected if VR/AR HMDs are to be reliably used. While most studies have found that cybersickness becomes more severe with increased exposure time, there is no agreement regarding specific lengths of time that clearly demonstrate a critical level of cybersickness.

Lo and So measured cybersickness at 5-min intervals in a VR HMD and found a strong increase from time 0 to the 5th minute, and a modest increase at the 10th and 15th minutes [136]. Another study by this group showed that sickness steadily increases during exposure in a 30-min experiment, however the only significant change was between the 5th and 10th minute [132]. Lo and So used the SSQ before and after

[25] This topic was discussed as a potential user characteristic in Section 5.1.4.1.5, so it is discussed only briefly as a stimulus-related factor here.

experiments and a nausea scale where participants verbally reported their nausea level on a Likert scale from 0 – 6 at various time points during the experiment. Hakkinen et al., examined SSQ scores of participants viewing stimuli of stationary environments with 360˚ viewing capability, allowing exploration of the virtual environment in a VR HMD at 5, 10, 20, and 30-min intervals [156]. Researchers found a significant difference in SSQ scores between 10- and 20-min durations. Many other studies have repeatedly shown a relationship between time in the experiment and increased cybersickness severity [157], [158]. Thus, there is general consensus in the literature that cybersickness is more severe with more time spent in VR. What is less clear is if and when cybersickness plateaus, and if adaptation to cybersickness (i.e., reduced cybersickness) can take place within a single VR exposure period. Some studies have found evidence for cybersickness ceiling effects, and even adaptation within and between test sessions (see meta-analysis in Refs. [159], [160], [161], [153]). Kennedy et al., described a method of repeated exposure to simulation tasks that has shown to reduce sickness [161].

A likely reason there is no consensus on the amount of time needed before an individual gets sick is because it depends on many factors that are not controlled across different studies as well as individual differences. For instance, Nesbitt et al., looked at participants that were in a high-fidelity (e.g., rich, and realistic graphic content) roller coaster condition and a low-fidelity (e.g., basic graphic content) roller coaster condition in a VR HMD [162]. They found that participants tended to become sicker faster in the high-fidelity roller coaster than in the low-fidelity roller coaster. Thus, in this study, fidelity appeared to be a factor that directly impacted the time course of cybersickness. Individual factors (discussed in detail in Section 6.1) and conditions of the operational environment listed here in Section 6.3 are just some examples of variables that directly impact amount of time before experiencing cybersickness with a VR HMD. However, there is general consensus in the literature that sickness increases with time spent in the VE.

5.3.9.2 Time Needed to Recover from Cybersickness Post-Experiment

Stanney et al., recorded SSQ scores at 15-min intervals during a 1-hr study [163]. They also examined SSQ scores 2, and 4 hours after the experiment and the next morning. Participants performed a battery of tasks while wearing a VR HMD in a virtual maze that they navigated through. Stanney and colleagues divided participants into those that finished the experiment and those that dropped out before completing the experiment. They found that individuals that dropped out of the study remained significantly more ill up to 4 hours post study compared to those that completed the study. However, even the participants who dropped out of the study were no longer sick the following morning compared to their pre-test scores. Greater evidence is available concerning simulator sickness, in which case 8% of trainees had symptoms 6 hours later [164], and some cases have been observed 18 hours post-exposure [165]. Dziuda et al., also found no difference between baseline and SSQ scores from the following morning in an experiment comparing cybersickness in a fixed-base and motion-base driving simulator [145].

There are many challenges with collecting cybersickness scores from participants after the completion of an experiment. Because the data is sometimes collected outside of the lab, the experimenter cannot precisely control when the data was recorded by the participant, what activities the participant performed that may impact sickness differently, and what substances the participant may have used or ingested that can affect cybersickness recovery. However, since cybersickness takes may not fully subside until the next day [145], it is wise to track this information as best as possible.

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Chapter 6 – MITIGATION METHODS

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6.1 DESIGN MITIGATION METHODS

This section will examine various approaches to mitigate harmful effects of cyber sickness from an application design point of view. For a VR experience to be designed to mitigate possible user's cyber sickness means to devise interaction mechanisms and visual techniques which somehow make the immersed user feel more comfortable in perceiving, moving, and interacting with/within the virtual environment with respect to human own sensory perception system.

6.1.1 Visual Realism

In an era of near photorealistic real-time 3D graphics capability, it might seem obvious to suggest pushing graphics to the highest quality possible – while safeguarding the HMD target frame rate / max latency – in order to make a VR user feel comfortable in a lifelike synthetic representation, and thus hopefully being less prone to sickness. It is intuitive that a high-level of visual realism is positive for raising the sense of presence in a credible operation environment and thus e.g., the effectiveness of the VR training. Nevertheless, some evidence has been found that a high visual realism of the scenes fed to VR users could lead to cybersickness more than the less realistic ones [1], [2], [3]. A first hypothesis for this is that graphically realistic scenes are more perceptually demanding, but another explanation has been proposed: as the visual stimulus becomes more similar to reality, the user is more immersed in the VR and expects vestibular inputs corresponding to the visual stimulation. However, users cannot acquire such vestibular information, so the degree of conflicts as well as VR sickness increases [1], [4], [5].

A mitigation suggestion on this topic is to be ready to downgrade at runtime the rendering quality to graphically simpler representations (e.g., disable effects, advanced lighting, textures, and so on) as discomfort phenomena arise in users in order to check if the excess of visual realism is their cause.

6.1.2 Body Perception / Embodiment

Embodiment, or self-embodiment, is the illusory sensation for a VR user of perceiving his/her own body counterpart in a virtual human body representation present in the virtual environment ("being there") [6]. Beside the natural look of the 3D virtual body representation, an effective own body perception requires that real and virtual bodies have to perfectly match both in time and in the 3D co-registered spaces. A number of parts of the real body (e.g., knees, feet, elbows, pelvis) have thus to be tracked other than the head and hands at a rate according to the HMD scene refresh rate, and the tracking+display system must make these to appear in a credible position to the user with respect to where his/her proprioception makes him/her believe that they are.

Whilst embodiment is clearly an effective comfort-rising strategy for a VR user, it remains unclear its relationship with cybersickness [7]. Nevertheless, implementing it in a VR app could be explored to mitigate the risks of possible disturbance implications related to not recognizing himself/herself in the VE.

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6.1.3 Limiting Visual Flow or Field of View

As counterintuitively as the case of visual realism, a large field of view is not always considered to have a positive effect on human performance in VR. It is a desirable feature when the scene around the user is almost static, and when there's no, little, or slow movement – either for a linear change of position or due to the rotation of the subject's point of view such as when he/she looks around. It comes out instead that, when the visual flow becomes substantial, the amount of scene motion perceived by the immersed user in the peripheral parts of the vision can lead to oculomotor disturbance and to cognitive overload.

When is not possible to reduce the visual flow by limiting the linear speed of the user's movement, and/or limiting the speed of the camera rotation related to user's head tracking, a trick is dynamically restricting the field of view by a graphic obscuration of the viewport periphery by a factor proportional to the speed magnitude [8].

6.1.4 Visual Acceleration

Linear or angular visually perceived accelerations, which do not correspond to vestibular stimulations, are particularly harmful in immersive VR as these are at the base of the so-called Visually-Induced Motion Sickness. In a VR simulator, these can occur when the user is on board a moving vehicle, and if there's no motion platform to stimulate his/her vestibular system accordingly, or when the visual and the simulator platform follow each its own rules for rendering their stimuli.

These camera-initiated movements and the corresponding visual accelerations have to be limited as much as possible for a VR application to be less cybersickness-prone. From this point of view, constant velocity is safe instead since the user unconsciously expects no impact on the vestibular system (refer to Section 5.3.5 for additional discussion).

6.1.5 Reducing Unexpected Movements or Showing Visual Leading Indicators

A cause of sickness for VR users is the sudden, unexpected change of direction in vehicle-attached camera movements. One for all, imagine a VR roller coaster simulator: along the way, a user is visually buffeted left-right, up-down, and maybe even physically solicited by a motion platform or other forms of shaking, and his/her disturbance is as high as he/she cannot foresee the next upset source.

Assuming that, in a VR app, unexpected movements, i.e., those not induced by the user, should be reduced to the minimum necessary, making the user mind anticipate upcoming changes of direction and related visual movements, when predictable, mitigates their suddenness and thus contribute to reducing the related discomfort. To this purpose, semi-transparent arrows or dotted trails can be overlaid to the scene as path leading indicators so actually acting as anticipation helpers of the upcoming visual movements.

6.1.6 Dynamic Focus / Dynamic Blurring

Despite the different depths at which objects/parts are laid out in the virtual scene, in a typical Computer Generated Image (CGI) all objects/parts appear to be in focus. The importance of blurring less-important areas of the scene in favor of the user's attention on the more important ones has been underestimated for a long time [9]. However, when designing such a focus strategy the problem arises on what criteria to base the choice of the focus depth range on.

Whilst impossible for the human sight in immersive VR to accommodate on a plane different from the one of the actual display screens, the convergence angle can instead be detected by eye tracking, which modern HMDs are more and more equipped with, thus enabling a dynamic focus strategy. Intersecting converging viewing rays with scene objects, the object/part of the scene the user wants to focus can be located by a heuristic model based on an importance function [9]. Then, by difference between its position in the scene and the camera position, the visualization system can find out the focus distance. Focusing "jumps" have to be managed adaptively in order to not introduce a further source of visually-induced disturbance.

6.1.7 Rest-Frame Cues

In a dynamically changing visual scene reflecting unintended camera movements in pitch and roll, the human proprioception system might be misled, and a VR user may feel disoriented. In such situations, graphics cues that remain almost stable in the foreground, or even fixed in the display viewport, helps the user as trusting references to objectively evaluate motion. The reason why rest-frame cues work for contrasting cybersickness is because the disoriented user can cling to them to trust something which is stably positioned in the scene, and/or to distract him/herself from the visual disorientation.

Among rest-frame cues, foreground cues are graphics representations locked to a certain position in the viewport such as a dashboard, a cockpit, a HUD, reference frames, or even simply a 3D virtual nose [10] halved in two in a stereoscopic pair that has revealed surprisingly effective in mitigating the disorientation in immersive VR [8]. Background rest-frame cues are, instead, representations that remain locked to the 3D scene reference frame and may include the typical panorama far-field elements such as the horizon, clouds, mountains, etc., whose space orientation the user trusts [11]. A third type of reference frame is one attached to the real world, which may be anticipated to have the largest mitigating effect. Which type of cue is most effective remains to be tested.

6.1.8 Viewpoint Control

It has been generally agreed that, for reducing the probability of cybersickness symptoms onset in an immersive VR simulation, the viewpoint must be preferably left in full control of the user. Leaving the user the responsibility for initiating and terminating movement makes him/her able to predict it and to anticipate its upcoming visual feedback.

As proven experimentally [12], teleportation has to be slightly preferred to steering locomotion as a user-controlled navigation technique as it can reduce the symptoms of nausea. For those users becoming disoriented anyway, it may be of help starting teleportation by a fade-out of the scene leaving point and ending it by a fade-in the new scene points so to limit the negative impact on the user of a raw scene change.

6.1.9 Reducing Vection: An Unproven Mitigation Method

Sections 5.1.4 and 5.3.8 reviewed the evidence for vection as a contributor to cybersickness and failed to find it compelling. The current literature does not consistently find vection to be a necessary or a sufficient condition for cybersickness or VIMS to occur, nor does it usually find a strong, positive correlation between vection and VIMS. Therefore, reducing vection is not a recommended countermeasure for cybersickness. This is good news, because it means that, provided the visual stimulus is designed and presented appropriately, the vection illusion can be exploited to quickly and inexpensively foster VR engagement by inducing a feeling of self-motion through the virtual world, when appropriate to the goals of training.

Although limiting vection may not reduce cybersickness, VIMS can be reduced by the following stimulus constraints which are more pertinent to the optical flow stimulus than the self-motion percept:

- **Limiting the acceleration and peak velocity** of ambient visual flow. This may reduce sickness by reducing oculomotor [13] and retinal slip contributions [14], [15]. Generally, slower-moving visual scenes tend to elicit vection quickly without much sickness [16], [17]. Presumably, this is because the ambient visual motion (which signifies self-motion) conflicts less with the vestibular cues, which are failing to signal self-motion.

- **Limiting the field of view** tends to decrease sickness, presumably because there is less visual-vestibular frame-of-reference conflict (e.g., as the visual scene accelerates, it is not as readily interpreted as a visual surround contradicting the lack of acceleration stimulus to the vestibular organs.)[2]
- **Limiting sudden changes in velocity and direction** of the visual flow field. As the field changes direction and velocity more frequently, it is likely to produce more sickness but less vection. Presumably, this is because vection does not have time to build to maximum saturation and compellingness prior to the next flow change, and because the changes offer repeated sensory conflicts to the vestibular system, which is signaling a non-moving or constant velocity body movement status.

In conclusion, while some of the visual stimulus parameters can be manipulated to reduce cybersickness, there is not good evidence that such manipulations reduce sickness via an intervening reduction in vection. Rather, it appears that they do so by reducing conflicts between visual and vestibular signals or expected signals, and possibly via a reduction in oculomotor activity. Conversely, when a moving visual stimulus is perceived as a stationary frame-of-reference by a stationary observer, the observer is presented visual information that they are moving and vestibular information (initially) indicates they are not moving. The interpretation that this stimulus specifies self-motion will contradict the vestibular signal initially (when actual acceleration of the body would be expected but is not occurring), or when a change in the direction or acceleration of the visual flow field occurs. However, if an ambient visual scene is moving very slowly at a constant velocity and in an unchanging direction not indicative of body tilt, then experiencing a vection illusion is a good solution to the visual problem presented and encounters very little conflict from vestibular expectations.

6.1.10 UTSA's GingerVR® Unity Tool Kit

John Quarles, an associate professor in the Department of Computer Science at University of Texas at San Antonio (UTSA), and his Ph.D. student Samuel Ang, implemented a number of visual techniques described in this Chapter and in Chapter 5 plus other techniques from research and collected these in form of Unity toolkit ready to be used for application development, and made available in open-source form [19].

The GingerVR® tool kit includes the following techniques for contrasting cybersickness, or motion sickness, during the use of Virtual Reality applications developed in Unity®:

- **SingleNose** and **AuthenticNose**: create a rest-frame for the user [10] (see Section 6.1.7).
- **DynamicGaussianBlur**: a script which dynamically blurs the user's vision based on their translational speed. The rotational speed of the camera determines the sigma value used in the Gaussian function [20] (see Section 6.1.6).
- **ColorBlur**: a script which dynamically blurs the user's vision based on their translational speed. Portions of the image surpassing the specified color thresholds (i.e., brightness) are not dynamically blurred [21].
- **DynamicFoV**: a script which dynamically reduces the user's Field of View (FoV) based on their translational and angular speed [8] (see Section 6.1.3).
- **DotEffect**: a prefab which suspends virtual orbs around the user which move at twice the user's velocity [22].

[2] Note, however, that vection can still be elicited with a small field of view expanding radially [18]. It may be that whether a visual flow field is considered an ecologically valid frame of reference is more important for vection than whether it has a large field of view.

- **HeadSnapper**: a prefab which detects when the user's head rotation speed passes a certain threshold, at which point their perspective is "snapped" in the direction they were turning. After a brief fade to black transition, the camera's orientation is locked, and then rotated by a specified angle along the y axis. The user's vision then fades from black so that they can see again [12] (see Sections 6.1.4and 6.1.8).
- **VisionLock**: a prefab that allows users to lock what they are seeing on screen with a button press. While the effect is active, the image users see will not change with head movement. This effect is currently limited in that all objects in the scene which you wish to rotate with the user's camera must be children of a single parent object, and because physics interactions in the scene are not rotated while VisionLock is active [23].
- **VirtualCAVE**: an asset that spawns a wireframe cube around the user. This cube follows, and rotates along with the user to simulate a cave automatic virtual environment. To use VirtualCAVE, simply drag the asset onto the user's virtual camera in the scene. The asset will spawn the wireframe cube at runtime. The following settings can then be adjusted through the editor [24].
- **FOVUtility**: a utility that allows to measure the user's Field of View (FoV), as Unity's Camera.fieldOfView does not currently support head mounted displays.

6.2 NEUROPHYSIOLOGY COUNTERMEASURES

Symptoms of motion sickness have been experienced by the unique visual-vestibular perspectives that accompany new forms of transportation; from sea travel to camels, automobiles to airplanes and now spaceships to virtual motion through cyber environments [25], [26]. One of the most effective mitigation strategies is the same as it was in ancient times; adaptation through repeated exposure to the sickness producing stimulus [27]. Therefore, the simplest and time-tested countermeasure for most of those afflicted by cybersickness is a gradual adaptation to the new demands on perception as one gets their 'sea legs' for the new motion. This section will begin with the behavioral mitigation strategies, like adaptation, reducing head movements, controlled breathing, since these are the ones, most often applied by those experiencing symptoms. Following that will be more direct, intrusive interventions that involve neurophysiological methods such as neuronal stimulation or pharmacological countermeasures. Finally, recommendations based on those mitigation strategies that seem to have the most support in the literature for efficacy in symptom reduction will be described in the conclusion and a sequence suggested for their applications.

The mitigation strategies discussed in this section for cybersickness draw heavily from the countermeasures recommended for motion sickness. This approach assumes that cybersickness, like motion sickness, is a disorientation of the visual-vestibular perception pathways induced by unusual perceived motions, only in the case of cybersickness, in a virtual environment, without physical movement [28]. Therefore, the countermeasures for one should apply to the other. This assumption remains to be tested, however, as cybersickness is a relatively new phenomenon compared to the ancient phenomenon of inertia-based motion sickness. One of the conclusions of this discussion must be that more research is needed that directly addresses the effectiveness of these strategies in virtual head mounted displays of the kind that will be encountered by NATO forces in training. As there is no completely effective countermeasure for motion sickness for all situations and individuals, none is expected for cybersickness. This chapter will show that there are methods that can dramatically reduce the incidence of symptoms for most people and most of the time.

It must also be mentioned that some degree of non-sickening stress from unusual motion may be warranted in cyber environments, particularly in training, to add to the immersion and realism. Vection, for example, may be desirable in some cases to foster presence in the simulated environment [29], [30]. Making virtual aircraft flight feel as much as possible like a real aircraft, would add to the virtual training at times. However, certain stimuli may prove too sickening for some trainees. If nausea is elicited in the real environment, being simulated, then some lesser symptoms may be desirable during simulation [31]. It may be that the occasional price of virtual realism in training is the risk of virtually-induced motion sickness.

6.2.1 Behavioral Training

Behavioral countermeasures include those strategies that require movement modification such as reducing head movements or limb movements, even standing [32]. These might be difficult to implement in virtual environments, particularly when training must be as close to reality as possible. The symptoms of motion sickness can be exacerbated by reading while moving or by excessive eating or drinking as well as by anxiety or emotional states [33]. The same is not known in cybersickness and, although likely, needs to be determined. The behavioral mitigation strategies are far more numerous than the neurophysiological strategies and should be considered the first line of defence in the countermeasure hierarchy as they do not require direct physiological intervention and are generally easier to apply. While effective for most people, these may not be the best option for cybersickness in cases where the time commitment for relief to occur is not possible. More short-term strategies such as limiting head movement or changing eye fixation may offer more immediate relief. However, strategies must be chosen carefully to avoid trainees learning strategies which would hinder performance in the real-world setting.

6.2.1.1 Head Movement

There is a strong relationship between head movements and symptoms of cybersickness. As with regular motion sickness caused by whole-body motion, there seems to be a direct relationship between the number of head movements in a virtual environment and the severity of symptoms [34], [35]. Head movements are more consequential in certain directions. For example, tilting the head in a driving simulation in the direction of the lateral forces in a turn can cause more symptoms than head fixation in the opposite direction of a turn [36], [37]. Also, inappropriately timed head movements to virtual displays of movement seems to increase symptom severity [27], [38].

There is general agreement that limitations in the FoV generated by VE equipment create an unnatural delay in movement perception and that the discrepancy can induce cybersickness. This could mean that head motions in VR could exaggerate the delay and create greater symptoms. There is also evidence that exaggerating head movements so that they approximate the enlarged FoV in VE (reducing the discrepancy) can reduce the behavioral and subjective consequences of the delay [39]. This was even more effective if head and hand movements were amplified to roughly compensate for the perceived discrepancies in FoV and hand motion during a tracking task. There would be some training time needed to accomplish the response quickly, but it could easily be accomplished in cyber environments and improve with use if it seems promising. This could prove to be the simplest and most effective short-term mitigation strategy, but specifics of the movement would have to be worked out.

6.2.1.2 Control Over Exposure

The degree of control one has over unusual motions may be another quick short-term strategy for mitigating motion symptoms [40]. The perception of control and predictability of unusual motion appears to reduce motion symptoms [41]. In a different context, exertion of control reduced motion sickness induced by playing video games on a tablet computer [42], [43].

In a yoked control study, two participants experienced nauseogenic rotation and the one controlling the motion and head movements suffered less symptoms than the passive control [44]. This strategy would require the individual drive the virtual vehicle or fly the virtual aircraft to experience control and the anticipation of what movements to expect before it happens. The extent of symptoms would be expected to be lessened, compared to those who cannot predict or control the movements [45], [46].

6.2.1.3 Eye Fixation

One of the most common strategies in controlling symptoms of motion sickness has long been to simply fixate the eyes such that the unusual motion visual cues are not evident [33]. For example, visual fixation on a target moving in relation to the head was less symptomatic than moving targets relative to the scene [47]. Eye fixation may be closely related to the effects of head movement since the vestibulo-ocular reflex is tightly coupled to head movements. A yet unsolved issue concerns the amount of visual-vestibular conflict interacting with eye fixation, implying that eye fixation may be helpful in some but counter effective in other conditions.

6.2.1.4 Diaphragmatic Breathing

Aircrew have often reported that relaxed and controlled breathing alleviated symptoms of motion sickness. One of the original studies of this effect found that controlled, slow, deep breathing induced parasympathetic responses and reduced tachygastria and other symptoms of motion sickness [48]. Similarly, another study compared controlled breathing to a counting task during a 30-minute exposure to whole-body pitch oscillations [49]. Controlled breathing allowed more to finish the 30-minute exposure with less nausea than the counting task. In another task, respiration rates in phase relation to the motion stimulus compared to spontaneous breathing was effective in controlling nausea [50]. The idea of controlled breathing is consistent with the idea of activating parasympathetic activity which is viewed as consistent with a reduction in stress or anxiety during mildly nauseogenic exposure and may partially explain why tranquilizing drugs, such as the phenothiazines (Thorazine, Phenergan) have an effect on motion sickness. These results suggest that stress reduction or relaxation training to counter nauseogenic stimulation could be another simple, quickly implemented short-term strategy for cybersickness.

It has often been reported anecdotally by aircrew that breathing supplemental oxygen reduced their symptoms of air sickness. Subsequent research found that breathing oxygen did not reduce the symptoms of nausea nor influence the recovery time from nausea, compared to normal air [51]. It may be that the reports of supplemental oxygen aiding in symptom reduction was a case of controlled deep breathing.

6.2.1.5 Using Music and Pleasant Odors

Other means that purport to relax an individual to during stressful cyber environments might be to use relaxing music or odors. In an immersive bicycle simulator, there was less susceptibility to unusual motion effects by music rated pleasant compared to music rated stressful or no music conditions [52].

The degree of symptoms was mild in both studies as was the effect. More severe environments were not tested. These strategies would also require externally applied music or odors that might interfere with the ongoing cyber training. Since the rating of pleasantness seemed to be the key to effectiveness of music and odors, it would be likewise difficult to find the more pleasant of these for each individual with symptoms. Evidence exists that other environmental influences can reduce the symptom severity of bicycle cybersickness. Increased airflow was effective in symptom reduction but not seat vibration [53].

6.2.1.6 Acupressure

Several popular devices use acupressure or electrostimulation, typically applied to the wrist, and delivered by vibration or mild shock for the treatment of sea sickness. Most of the literature in reputable journals suggests either no discernible effect or are barely distinguishable from placebo [54], [55]. A few have reported effects, particularly in the P6 meridian, between the two median tendons on the wrist [56]. The evidence does not support these treatments and they could prove distracting in a cyber training environment. In addition, it is not clear how the underlying theory relates to known physiological and neural processes.

6.2.1.7 Motion Habituation

Behavioral countermeasures to motion sickness may be broadly classified into immediate, short-term behavioral modifications, such as those just described and habituation techniques [27]. Habituation offers the surest countermeasure to motion sickness but, by definition, is a long-term approach. On ships and in space, this can occur within a few days [33], [57]. The effectiveness relies on short duration exposure until uncomfortable symptoms begin and then repeating this, after complete recovery, for longer exposure durations. This regimen seems to work in VR as well [58], [59].

Habituation to motion environments may parallel early experiments in optically adapting to distortions in the visual field [60], [61], [62]. It has been well established that wearing prismatic or mirrored goggles (for example continuously for days) elicits a remarkable adaptation in which visually-based motion errors decline continuously and behavior returns to normal [61], [63], [64]. One conclusion from these and other such experiments is that the visual-vestibular and kinesthetic senses are able to quickly recalibrate when actively interacting with a visually disturbed environment so long as the environment remains constant over time [65]. This conclusion has been made for virtual environments as well [66], [67].

There seems to be a strong individual component to this rate of adaptation [67] and the rate seems to be consistent within individuals across different measures of motion sickness [68], [69]. Sex and age don't seem to be a reliable factor in adaptation rate [62] although few studies have examined elderly individuals.

The visual and behavioral adaptation to a distorted environment is remarkable in that it occurs quickly, resetting a lifetime of normal visual experience. Many experiencing the discomfort of cybersickness terminate their experience without slowly trying to adapt to it. The evidence shows that the adaptation is a long-term phenomenon, if established [70], [71], and may strengthen the longer it is continued [72]. There is good evidence of cross adaptation in that exposure to one visual condition, significantly reduced the adaptation rate in another but similar condition [73]. The implications are that a) habituation to nauseogenic stimuli is possible and rapid, although with a strong individual component and b) that habituation may generalize to a similar but not identical environment. With regards to the last point, one could conceivably train repeatedly on a milder version of the virtual stimulus that is causing the nausea and rapidly adapt to a comparable but more difficult stimuli. Research remains to determine the limitations and characteristics of these implications for cybersickness but habituation is, and has always been, the safest, simplest means to overcome the symptoms of distorted motion.

The U.S., Canadian, Dutch and Italian military have developed extensive habituation programs that desensitize motion sickness response in susceptible pilots and sailors with success rates greater than 85% [74], [75], [76], [77], [78]. However, these can take many weeks to complete.

The military has desensitization protocols that prepare people for flight duty who are resistant to drug remedies. Experienced pilots were found to more than halve their symptoms after 5 successive days of nausea induced by G-training [79]. Uncontrolled eye movements during the unusual motions in a centrifuge have been blamed for the nausea. Remarkably, these protective effects lasted over two weeks.

Habituation to a virtual environment, however, seems to be successful at the cost of an increased postural instability. Kennedy and Stanney [80], for example, noted an increased chance for falling (ataxia) after repeated simulator exposures, as did Bos et al. [81] after watching a single 3D movie in a cinema. The latter also observed that, despite a significant decrease of sickness, postural instability lasted for (at least) an hour afterwards. This is consistent with simulator research, which has found lasting balance-related symptoms (and other symptoms) lasting more than an hour after the end of exposure in 25% of pilots [82].

6.2.1.8 Operational Time Limitation/Desensitization

While motion sickness and anxiety are two different phenomena, they share some symptoms in common. Also, sickening situations can elicit anxiety. A more complex behavioral strategy might be considered for cybersickness-like symptoms that are related to stress or anxiety. Users might be aware of their sensitivity to cybersickness and become anxious of disqualification from training or of embarrassing themselves. User also may have gained a classically conditioned anticipatory response to the sickening situation, which includes anxiety and associated anticipatory symptoms at the mere sight or smell of the eliciting device or circumstance. Forms of counter conditioning have been used very successfully as a behavioral treatment for anxieties and stress for over 40 years [83], [84], and, for example, airsickness [77]. These techniques first train the individual in muscle relaxation and regular breathing techniques with pleasant visual imagery [85]. Then they increasingly approximate the anxiety producing stimulus. Over several days of countering less stressful behaviors with stressful stimuli the response of symptoms can be counter conditioned or replaced with relaxation [86], [87], [88].

The U.S. military has successful airsickness mitigation programs involving a variety of motion countermeasures. Depending upon the branch of service, such programs may involve a brief trial of anti-motion sickness medications during the first few flights following sickness, followed (if necessary) by education concerning motion sickness (causes and mitigations), many sessions of adaptation to head tilting during rotation, and other approaches such as biofeedback. The U.S. Navy program has a success rate of ~85% [75]. While the degree of variance accounted for by each of these measures is not known, it is likely that carefully controlled incremental motion adaptation to (Coriolis cross-coupling head tilts in several directions during passive body rotation) comprises a general enough MS desensitization to permit transfer of adaptation to flying. Nevertheless, in cases where aversive conditioning has taken place and the pilot reacts negatively to the site of the aircraft or smell of jet fuel, training to break that negative response is warranted.

A newer form of counter conditioning is Cognitive Behavioral Therapy (CBT). It is distinguished from the traditional forms in that, rather than imagining pleasant visual imagery, other thoughts are used such as thinking about numbers or poetry or distracting one's thoughts from the stressful stimuli to. This success of these counter conditioning treatments in stress reduction implies that they could be successful in mitigating the stress or anticipation of cybersickness which then may reduce these secondary symptoms. While we were not able to find evidence that they have been tried with motion sickness, at least one study provided the evidence and means to do the studies [89].

These techniques can help in cases where secondary symptoms have arisen due to anxiety or aversive conditioning, but they are time consuming, and they require a level of concentration which renders them difficult to apply in a high-tempo operational situation where sickness has already arisen. In some cases, the fact that a considerable amount of time is needed to acclimatize the user slowly could be an asset as more time for habituation would also occur, combining strategies.

In some cases, the fact that a considerable amount of time is needed to acclimatize the user slowly could be an asset as more time for habituation would also occur, combining strategies.

6.2.1.9 Individual Information Flow Adaptation

Symptoms of motion sickness can be reduced in a projection-based virtual environment by using Earth-referenced rest frames [90]. These rest frames are suggested to produce the effect by allowing the user to maintain some reference, some perceptual contact with the real world and to lose the sense of immersion. Keeping fixed visual outside references, for example, in a projected or HMD cyber experience reduced symptoms during strong rotational motions compared to no references [91]. Consistent with the idea that simultaneous perception of normal, real-world frames of reference during perception of the virtual environment reduces the experience of motion symptoms is the HoloLens. In a study of motion sickness symptoms, when users could see both the cyber environment and the real environment via a HoloLens and only negligible symptoms occurred [92].

Healthy users (but not vestibularly-impaired individuals) experienced less motion sickness in visually provocative environments when an artificial horizon was projected to one eye that was aligned with the head and body position [93]. One eye perceives a real world and the other the virtual world. However, Feenstra et al. [94] found a reduction by a factor of two when projecting an artificial extended horizon that cued 6 DoF of motion). This result increased to a factor of four when adding an anticipatory motion trajectory. These studies suggest that veridical (real-world) sensory cues may reduce symptoms. Maintaining information about the horizon may offer some resistance to symptoms in individuals with a functioning vestibular system.

Manipulating either the amplitude or frequency of visual oscillations, and holding the other variable constant, showed that amplitude changes produced more symptoms than the frequency [95].

For naïve gamers, a study found that a thorough narrative about what they were going to experience in the game reduced their nausea, eye strain and disorientation compared to a simpler narrative [96]. This effect was not found in experienced game players. The authors attributed the effect to knowing what to expect, which reduced inappropriate head and eye movements, hence reducing sickness, but of course, experienced players should already be more adapted to the situation, so perhaps they had less room for improvement.

6.2.1.10 Conclusions

The effectiveness of behavioral mitigation strategies in the short term for immediate relief seems related to the appropriate voluntary control of head and/or eye movements in the cyber environment. The more the individual is in control over the unusual motion or the more predictable the motion is, seems to be help reduce symptoms. If there is time to train, habituation and desensitization techniques seem to work well and last for a while. It may be useful to develop increasingly nauseogenic stimuli for a training device to acclimate the users who experience cybersickness. Repeated exposure to the stimuli, stopping the simulation before they symptoms become too great and repeating the exposure to extend that stopping point may be a useful training strategy. Knowledge of what to expect may play a role in helping to control inappropriate and symptom enhancing visual and spatial misperceptions that could exaggerate the symptoms. An important adjunct strategy, perhaps combined with another mitigation strategy such as adaptation, would be to relax. The use of relaxation techniques in the presence of stressful stimuli, through deep, controlled breathing or more formal relaxation training, seems promising in reducing symptoms.

6.2.2 Neurophysiological Intervention

Most people will experience cybersickness to varying degrees in a virtual environment. The preceding section described effective behavioral strategies that would require the user perform or modify normal reactions to unusual motion stimuli to alleviate the symptoms. The current section will describe neurophysiological mitigation strategies that imply a quick but invasive intervention that typically requires monitoring the user for side effects. They will also work for most individuals but should only be tried when behavioral mitigation training has not worked.

6.2.2.1 Nerve Stimulation – Haptic/Galvanic/Magnetic

Transcranial Direct Current (TDCS) and Galvanic Vestibular Stimulation (GVS) have been reported to be successful in reducing cybersickness symptoms, presumably through adding ‘noise’ to overwhelm or mask ‘confused’ vestibular signals (Section 6.4.2) [97], similar to the beneficial effect of mechanical vibration added to the head [98]. Others have found that mechanical vibration to the head can also elicit symptoms [99]. Since galvanic and vibrational stimuli can either reduce or exacerbate motion sickness, it is important to design and implement these countermeasures carefully.

While lower symptom ratings are reported during stimulation, these effects typically only last for a few minutes after exposure before symptoms return. Although there are several devices that send electrical or mechanical pressure transcranially, purportedly from the one vestibular organ to the other through the head, doubtless other CNS circuits are also affected. These methods produce noticeable side effects on behavior such as twitching or stumbling which only lasts for the duration of the stimulation but can disrupt the immersive experience as well as normal behavior such as walking. Similar results were found using bone conduction of mechanical stimulation to presumably interfere with 'incorrect' vestibular signals and the effect could be enhanced if the projected image was angularly accelerated [98], [100]. It has been shown by others that bone conduction and presumably electromotive or galvanic stimulation, causes linear acceleration perceptions from the otolith organs [101]. The disadvantages of these stimulation techniques, in addition to the extra vestibular stimulation effects, arise from the need for a headset to go under the cyber equipment and that some may become uncomfortable with the invasive stimulation methods.

6.2.2.2 Nerve Stimulation – Information Masking

It may not be necessary to use transcranial stimulation to alleviate cybersickness. The use of tactile stimulation to resolve spatial disorientation, particularly in flight, has been known for some time using vibrotactile belts, seats, or vests [102]. Tactile stabilization of posture has been found from light fingertip vibrations [103]. Blindfolded individuals were shown to reduce postural sway by as much as 50% using fingertip stimulation. In addition, persons who had lost labyrinthine function were shown to stand indefinitely with eyes closed after the tactile stimulation ceased [104].

The effect on postural stabilization from tactile stimulation occurs within a 100 msec, more rapidly than visual stabilization methods [105]. Tactile stimuli have been used to mitigate spatial disorientation [106] but the effect on cybersickness reduction has not been the focus of these studies (e.g., Ref. [107]). Light tactile stimulators could be placed on various parts of the body to indicate movement and direction and this added cue might help to overcome the disorientation of virtual motion and hence, cybersickness.

For vertigo that is hard to treat, a device called a Meniett pulse generator was developed to apply pressure to the middle ear and, presumably, to lessen fluid build-up and produce the effect. Treatment involves application 3 – 5 times a day for 5 minutes at a time. This therapy has shown relief of vertigo, tinnitus, and aural pressure in some studies, but not in others. Its long-term effectiveness hasn't been determined yet.

6.2.2.3 Pharmaceutical Intervention

Pharmaceuticals[3] are used to relieve cybersickness symptoms that are persistent and severe. The importance of anti-nausea and anti-emetic drugs cannot be overstated in situations where a mask could be clogged such as post operatively or during aircraft maneuvers.

A variety of compounds have been used over the last 30 years to alleviate motion sickness in nauseogenic environments [111]. The majority of these consist of anti-muscarinic drugs, such as scopolamine (hyoscine) typically delivered as a patch, and antihistamines such as Bonine (meclizine), Dramamine (dimenhydrinate), or Phenergan (promethazine). The antihistamines are more familiar as they are non-prescription medications but of little clinical significance [112], [113]. Scopolamine, especially when combined with d-amphetamine, appears to be better at preventing motion sickness than any of the antihistamines [112], [114]. However, no known medication will entirely eliminate sickness in severe situations, and there are important operational military considerations surrounding the use of transdermal scopolamine [115]. In addition to its antihistamine and anticholinergic functions, promethazine, a phenothiazine, also acts as a Dopamine (D2) receptor antagonist [116]. The additional effects of promethazine beyond the H1 receptor site could explain its superiority over other Histamine (H1) antagonists. NASA uses scopolamine/d-amphetamine combination

[3] Potential nutraceuticals (e.g., ginger) and alternative medicine interventions (e.g., acupuncture/pressure) often come up when pharmaceuticals are discussed. The evidence for these countermeasures is mixed [108], [109], [110].

and Phenergan for difficult cases of space motion sickness. These drugs work well but have unwanted sedative side effects. Relatively few studies have looked at operationally relevant abilities under controlled circumstances, but one study involving simulated shooting did not detect functionally relevant decrements under a variety of anti-motion sickness drug conditions [115].

Proponents of ginger root extract, as a natural anti-nausea medication, have been around for centuries. It was reported to be used by the Chinese as long ago as 400 BCE as a medicinal for many purposes, including seasickness [98]. The effects of ginger on motion sickness have been well tested and are equivocal at best [108], [109]. Like many compounds with little clinical evidence of efficacy, ginger has remained popular as a recommendation because of a 'false positive' effect; if, after taking it and one doesn't get seasick, it is easy to attribute it to ginger when it could just as well have been that sea conditions didn't produce seasickness, no matter what was taken. The user then becomes an advocate of ginger [117], [118], [119], [120], [121], [122].

The disadvantages of pharmaceuticals to mitigate motion sickness are primarily their sedative actions, amnestic properties or, as in the case of the antihistamines, their clinical reliability. However, when sufficient time to habituate to the cyber environment is not possible then pharmaceutical intervention might be recommended.

Pharmaceuticals are one of the most available, simple, and effective ways to reduce cybersickness, provided they are initiated well ahead of predicted exposure. A wide variety of compounds have been used over the last 30 years as a prophylaxis to alleviate motion sickness in nauseogenic environments [111]. The majority of these are the anti-muscarinic drugs like scopolamine (hyoscine) typically delivered as a patch, and the antihistamines such as meclizine, dimenhydrinate, or promethazine. The antihistamines are more familiar as many are non-prescription medications.

6.2.2.4 Placebo Effect

Researchers go to great lengths to compare medication effects in double-blind, placebo-controlled studies. In a well-designed study examining specifically for placebo effects, ginger was compared to placebo during conditions that used levels of verbal expectations [123]. The study found no ginger effects nor expectation (placebo) effects, but changes in symptoms were found based on interaction with the sex of the experimenters.

In another study, participants were told that a pill would either increase (nocebo) or decrease (placebo) symptoms [124]. Those given the nocebo had fewer symptoms than placebo, even though it was the same pill in both cases. In a subsequent study, males were told a pill would increase symptoms (nocebo) and they showed lowered tolerance for rotational experience but no effect on symptom ratings [125]. The same group found nocebo responses in a rotational chair paradigm [126]. There do not seem to be strong placebo effects in motion sickness research but these authors caution about carefully controlling interactions and making use of double-blind techniques.

6.2.2.5 Conclusions

The most effective anti-nausea drugs, currently in use by the military are scopolamine and Phenergan. It is recommended that if pharmaceuticals are being considered for an individual, to prolong the exposure time due to a reduction in symptoms, that these be ground tested first on the individual. Ground testing should be done under medical supervision and ensures that the individual will not have a reaction during training. Typically, 24 hours should pass before the drug could be considered safe to use on the individual. Additionally, it seems that the behavioral strategies should be exhausted first before the more obtrusive medical strategies are attempted.

6.3 VR HORIZON SCANNING – PROTOTYPES, PRE-COMMERCIAL PRODUCTS, AND PROMISING TECHNOLOGIES FOR CONTRASTING CYBERSICKNESS

6.3.1 Otolith Labs Anti-Motion Sickness Integratable Technology

Following on a first paper showing a mitigating effect of head vibration on motion sickness [127], OtoTech® commercialized a head-worn, strap-on, bone-conducting transducer that uses white noise vibrations to provide consistent, noninformative stimuli to the vestibular system. These vibrations prevent the spatial discordance, which is the root cause of motion sickness, resulting in a dramatic reduction of VR sickness in users. Samuel Owen developed OtoTech® through his company Otolith Labs, Owen said they have observed no other effects of the gadget other than your brain being more comfortable with simulated movement [128]. This technology is currently going through the stages of research approval through the U.S. Food and Drug Administration (FDA), if approved, this technology could have the potential of reducing Virtual Reality (VR) sickness in training simulators for various DoD partners. The prime company that has subcontracted Otolith Labs is VR motion, this company has claimed to have various successes in reducing VR sickness. In fact, CEO Keith Maher told reporters that they have historically seen a 20 – 30 % sickness level among trainees [128], which was captured during their research efforts. It will be interesting to see whether this newly constructed device will in fact reduce VR sickness in during controlled experimentation by third parties.

6.3.1.1 Potentially Related Research Study

Queens University in Canada conducted a research study that utilized Bone-Conducted Vibrations (BCV) to help reduce the levels VR sickness. The method they used involves applying noisy stimulation to the vestibular system using Bone-Conducted Vibration (BCV) that is applied at the mastoid processes [129]. This relevant study reflects a similar approach to that of the strap-on device that Otolith Labs has developed, granted OtoTech® is focused on white noise vibrations, Weech et al.'s study [129], on the other hand, focuses on bone-conducted vibrations which may or may not be correlated. Experiments conducted in the study focused on aerial navigation using oculus plugin in Unity 3D and low-cost infrared hand-tracking camera Leap Motion Controller, Version 3.0.0, [129] while the other utilized a large projector and gaming controller. Essentially, the researchers generated a path for participants to navigate by positioning 30 spherical targets in the environment [129]. Students who participated in both experiments found that BCV did in fact help reduce the levels of VR sickness. In fact, the study showed in both Experiments 1 and 2 that participants exhibited less simulator sickness in the condition where vibration was coupled with angular accelerations of the camera compared with control (fewer than half experienced SSQ scores of 20 or above) [129]. However, some of the VR sickness susceptibility occurred during experiment 2 when the hand-tracking camera connectivity was lost. Many times, if the hand tracking did not work students would not be able to maneuver the aircraft. Furthermore, there were a number of participants that reported 'fatigue' and 'general discomfort' at least once 85% and 72%, respectively [129]. This may have also added to some increased level of VR sickness. These are various factors that may need to be analyzed when defence members are conducting potential experiments in the future as it relates to BCV.

6.3.2 NVidia® Lightweight VR Gaze Tracking System Using LED Sensors

NVidia has constructed a VR eye-tracking system using LED sensors. Although this prototype is going to be very large and costly, it may help reduce VR sickness for potential users due to increased eye-tracking capabilities. This prototype has the ability to both emit and sense light – to simplify the process of determining the eye's position relative to a display [130]. This approach has been used before, but NVidia's approach may be beneficial as LEDs also are used for color-selective sensing from the same location [130]. Furthermore, LED lights surrounding the eyes emit a range of light rays within the infrared spectrum. LEDs also consume little power and rely on comparatively simple controller hardware and software, they cut overall latency, reduce the number of cameras needed by the headset, and remove the need for an extra image processing block within the headset's pipeline [130]. This prototype is still in the research stages; however, it may improve eye-tracking capabilities and reduce VR sickness for various consumers. Defence readers should definitely keep an eye out for this this new technology that NVidia is experimenting on.

6.3.3 PlayStation® VR Motion Sickness Technology

PlayStation® constructed an experimental evolution of its VR headset that has the capability to monitor VR sickness susceptibility in a user and advise him/her on when to remove the headset before the insurgence of severe cybersickness consequences. The new PlayStation VR® tech would use a variety of biometric, moisture, and orientation sensors, as well as advanced eye-tracking cameras, to detect when a player is about to enter in pre-sickness state. The devices sensor configuration consists of various warnings features to help inform players of potential VR sickness risks. Users will receive a visual/audible warning and/or some of the functions of the head mounted display may turn off [131] if it senses that the user is at risk of VR sickness. Granted this does not help prevent VR sickness, but rather informs players to pause and take a break from VR gaming prior to potentially getting sick. One key factor to acknowledge is that this device is a patented product constructed by Sony [132]; therefore, a potential research collaboration with Sony may be a potential advantage for defence partners. Although the concept of incorporating a VR monitoring system for military training simulators doesn't necessarily reduce VR sickness, it still could be of value in VR sickness realm.

6.3.4 Half Dome® 2 and 3 Varifocal VR Headset Prototypes

Facebook® scientists have developed a prototype headset known as the Half Dome 2®, which is a small headset with a 140° field of view and an adept Varifocal system, which has been shown to provide a clearer video quality within a VR application. The Half Dome 2® has a varifocal system that consists of a new type of liquid crystal lens made from a thin, alternating stack of two flat optical elements: Polarization-Dependent Lenses (PDLs) and switchable half-wave plates [133]. With a narrow stacked PDL structure, this allows the user to easily adjust the headset focus with very limited blur or visual limitations. Essentially, with the six liquid crystal lenses, the system can cycle through 64 focal plans (the number doubles with each additional lens) for smooth transitions between focal depths [133]. This allows players to see the finer details of certain objects within the VR setting, thus having the potential of reducing sickness within virtual reality. Furthermore, Facebook is already beginning designs for the Half Dome 3®, which is planned to not only be smaller than its predecessors, the Half Dome 1® and 2®, but will also eliminate more noise and vibrations. Defence users may benefit from Facebook Half Dome 2® and 3® prototypes, as they continue to improve the visual capabilities in VR via their varifocal system; thus, potentially helping reduce VR sickness in training simulators in the near future. As with public users, defence users should be fully apprised on any data being gathered by corporations, and confident in the uses of such data.

6.3.5 WalkingVibe®

Scientists from the Taiwan University created an experiment noted as the WalkingVibe® [134] to test whether active visual, sound, and tactile cues would help reduce levels of VR sickness in their participants. Essentially, this was a 240-person study to compare 4 vibrotactile designs with 3 audio-visual conditions and a tactile condition with PhantomLegs®, the authors previous work [7]. Participants were placed in a seated chair, with an upgraded HTC Vive Pro Eye® and told to walk through the various virtual scenarios. The study showed timing and location for tactile feedback had significant effects on VR sickness and realism [134]. Furthermore, the use of synchronization by means of visual, audio, and tactile vibrations has been shown to improve participants experience in the virtual realm, as represented in the study. In fact the study results showed that the tactile conditions (i.e., 2-sided tapping (synchronized), 2-sided vibration (synchronized and random)) significantly reduced participants' VR sickness – compared with two visual-only (with and without head-bobbing), audio, and backside vibration (synchronized) conditions [134]. The utilization of synchronized walking vibrations and audio were inherently better tools that helped reduce VR sickness and improved overall realism and experience within the virtual environments. The WalkingVibe® prototype still requires much work as scientists continue to improve the audio and vibration testing at 150 Hz for future studies. A rudimentary spatiotemporal cue such as this should not be confused with a full tactile orientation suit or vest. Defence partners may still find that there is a benefit to embedding audio, visual and a vibrotactile synchronization systems within a headset to potentially help reduce VR sickness for their military simulators, however this would eventually have to go through a validation process.

6.3.6 The HP Reverb G2® Omnicept® and Other Sensors-Integrating HMDs

Built upon the basis of the visually-excellent HP Reverb G2®, the Omnicept® Edition [135] – which is expected to appear on the market in Spring 2021 – add a number of sensors for monitoring the wellbeing of the immersed user such as eye tracking and pupillometry (by the Tobii sensor, which actually measures muscle movement, gaze, and pupil size), heart rate, and a face camera. An Omnicept® platform then collects and analyzes all these data in real-time with machine learning algorithms, delivering high-level insights. Training applications could take advantage of measuring a user's cognitive load (determining how much "brain power" a user is exerting on the task at hand) thus giving a better understanding of the trainee's performance and ability to make decisions and/or delivering experiences that better prepare teams to deal with high-risk situations such as dismounted soldiers. Furthermore, with these integrated sensors, VR applications can track user engagement and assess user responses at any moment, and, with the face camera, avatars can display authentic facial expressions. From a cybersickness reduction point of view, Omnicept® sensor data can be monitored to analyze and promptly detect the insurgence of VR-related illness and has the advantage of a highly integration of body sensors within a state-of-art head mounted display unit in a commercial grade product.

Maybe the ultimate mode of capturing a user mental state for measuring a user's cognitive load is collecting data through a real BCI-BMI, whose integration into next generations VR HMDs is expected in one to three years (research-oriented products from LooxidVR address both PC VR headsets – in form of an add-on – and mobile-powered VR headsets combining eye-tracking and dry EEG electrodes for capturing brainwaves). Valve, OpenBCI and Tobii announced the launch of a VR Brain-Computer Interface named 'Galea®' in early 2022, for experimenting with neural interfaces on the basis of the Valve Index PC HMD®, and, to hear to Valve CEO, "to solve VR motion sickness and to increase immersion".

6.3.7 Case Study: Virtual Reality Pilot Training Simulator

The U.S. Air Force Research Laboratory's (AFRL) Gaming Research Integration for Learning Lab® (GRILL®) has been a key proponent and developer of game-based training utilizing commercial game engines and virtual and augmented reality approaches to provide dynamic and effective instructional solutions to Warfighter. The GRILL® team has extensive experience in developing custom training solutions with advanced technologies in multiple application arenas, such as undergraduate and helicopter pilot training. Both training simulator utilize Prepar3D® Professional Plus V4 Developer License, HTC Vive Pro Eye®, GeForce 2080 Ti®, gaming chair, stick/throttle, and rudder pedals for training purposes. GRILL® engineers have received feedback from various pilots noting that they have experience little to no VR sickness in our simulators. Some of the key features that may limit VR sickness are but not limited to, the simulators realistic aircraft and landscape visuals, its stationary positioning and the well-designed gaming chair and software/hardware add-ons. This highlights that a low-cost training simulator could be used to help reduce VR sickness as well as effectively train pilots during training scenarios, as observed by the engineers.

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Chapter 7 – GUIDELINES

Ben D. Lawson, John French, Paolo Leoncini, Peder Sjölund, Ramy Kirollos[1]

7.1 GENERALITIES

This Chapter presents recommendations for mitigating cybersickness in military personnel during training.

Firstly, recommendations have been identified for **preventing** cybersickness in regards the individual characteristics. Then, Operational recommendations, i.e., applying to the actual use of VR systems, have been also identified, subdivided into three phases: **Before** the usage of a VR system, **During** the usage, and **After** the usage. Finally, recommendations have been identified for the **Design** phase of the VR Systems, which include technological aspects of the VR equipment involved.

7.2 RECOMMENDATIONS ON PREVENTING INDIVIDUAL CYBERSICKNESS

We have made specific recommendations concerning many of the candidate variables considered individually early in this Report (see Section 5.1) and have voiced overall recommendations based on the meta-analyses and modelling studies reviewed above. Below are our practical overall recommendations for how to proceed in the operational military context concerning the development of user characteristics to accurately predict visual/motion sickness.

- Research, training, and operational uses of VR, AR, and simulators should consider the role that individual user characteristics play in a user's severity of sickness response, effectiveness of the technology for the intended purposes, and assessment of readiness of the user for other duty immediately following exposure to the technology.

7.2.1 Primary Predictors

- Chief among the most useful and practically implemented predictors of individual susceptibility which should be traced are estimates of MS severity during past exposures to comparable stimuli (e.g., past symptoms in similar motion situations, past symptoms during controlled laboratory stimuli, or, failing these sources of direct evidence, survey scores concerning one's past history of susceptibility across many different commonly encountered situations. Researchers can use such information as statistical covariates to improve the analysis of the influence of non-individual variables (such as stimulus refresh rate), while trainers can use such information to design optimal individually-tailored stimulus trial durations and break periods.

7.2.2 Possible Secondary Predictors

- A secondary variable worth exploring is field dependency. This is a possible but complex predictor of susceptibility. Moreover, it may not always be feasible to assess outside of the research setting and is not essential to assess if a primary predictor (e.g., past reaction to the stimulus of concern) is known. Nevertheless, this variable could capture a unique portion of the variance [1] and seems particularly relevant to VIMS, since it entails the measurement of the influence of a visual frame of reference.

[1] To cite: Lawson, B.D., French, J., Leoncini, P., Sjölund, P., Kirollos R. (2021). Guidelines. 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, Chapter 7.

- History of headache/migraine is a possible predictor with some positive findings in the literature. Considering the problem of concussion and vestibular migraine in the military [2], this is also a military-relevant variable to explore and is readily feasible for exploration in a military setting (via a simple question or a medical doctor's assessment of the patients online medical record).

- Another predictor is likely to be family susceptibility (or heritability) to motion sickness, which should be explored further in research studies.

7.2.3 Other Lesser Variables to Explore

- Variables which could be tracked by researchers to refine the general state of current knowledge and rule out interpretation confounds in cybersickness studies include age, sex, anxiety level, state of habituation, and state of aversive/classical conditioning.

7.2.4 Operational Caution

- Anyone considering operational implementation of any of the user predictors mentioned in this Report is urged to refer to Section 5.1.2, concerning the many reasons for caution. Another excellent source is Kennedy et al. [1], which provides further discussion of why the findings have been so mixed in the literature concerning individual user characteristics as predictors of motion and simulator sickness.

7.2.5 General Research Recommendations

- In general, the most useful prediction results will be obtained if future research focuses on controlled experiments instead of surveys, employs only the most reliable measures, uses large samples, elicits functionally-relevant levels of sickness, controls better for confounds (such as arousal/anxiety), and exploits multivariate predictor models for greater total prediction. These are the best means by which laboratory research will be produced that has good transition to applied science and technology (also see Chapter 8).

7.2.6 Keeping User Characteristics in Proper Context

- Individuals vary so widely in their susceptibility to visual/real motion sickness that it is possible for one person to be pleasantly amused by a stimulus that makes another person severely nauseate. Nevertheless, user characteristics should not be presumed the dominant drivers of sickness, nor considered in isolation when attempting to understand visual/real motion sickness. In almost every case, the sickness experienced by an individual will be a complex function of their inherent traits, their behavior/tasks during the stimulus, and the incoming stimulus itself. Regarding the stimulus per se, it has been hypothesized that stimulus exposure duration and length of time between exposures comprise temporal factors which account for considerable variance in sickness outcomes, apart from other factors [3].

7.2.7 Behavioral Training

The strategies listed here are the recommendations based on Chapter 6 and based on the evidence presented therein. There are some mitigation strategies not listed here because the evidence was not strong enough to consider them viable. Trainers should make the final determination as to how to proceed for their organization's VR applications based on a review of Chapter 6 and the recommendation here. We suggest records be kept concerning what works and what does not, while being aware that there will be many individual differences. Sharing of this knowledge and working on joint research projects is encouraged (see Chapter 8).

- Monitor exposure to new virtual environments to discover which areas of sensitivity are common and which are unique to individuals. Determine which individuals can adapt to them or if software or other mitigations like those discussed in this section are needed.
- Adaptation (sometimes called desensitization or habituation) techniques are the most common behavioral mitigation strategies and have proven the most effective over the centuries against motion sickness.
- Adaptation techniques require repeated and measured exposure to the challenging stimuli, allowing time for recovery in between, to determine if the sensitivity can be reduced.
- Employing other adjunct strategies during exposure to the operational event (e.g., reducing head movements, initiating deep breathing, focusing on non-moving elements of environment, allowing greater stimulus control by the individual) can be explored in concert with pre-adaptation techniques, to determine if motion sensitivity for the event can be reduced further.

7.2.8 Neurophysiological Intervention

- If pharmaceuticals are needed, test individuals for reactivity to doses recommended for motion sickness (e.g., for scopolamine or promethazine) prior to use as anti-nausea drugs during real or visual motion. Baseline testing should be done once, under medical supervision.
- Administer if drugs are needed to provide resistance to the symptoms of motion sickness during training.

7.3 RECOMMENDATIONS ON USING VR SYSTEMS

7.3.1 Before Using VR Systems

- Users should be given ample time to adjust the HMD lenses to match their own interpupillary distance as much as possible. Not many HMDs adapt to small interpupillary distances, thus the choice of a particular HMD can be critical here, especially for smaller users.
- If allowed by the HMD, also adjust the focal plane distance by moving the display plane away/closer by the proper knobs, or, alternatively, consider keeping your glasses on if there's enough space in the HMD (hopefully, it is designed to do so).
- Approach the user to virtual environment gradually in order to foster habituation.
- Reduce symptom occurrence in difficult cases by pharmacological means (i.e., anti-motion sickness medications).

7.3.2 During VR System Use

- Duration of VR use for military training should be limited as much as possible to reduce cybersickness, in sensitive individuals. Consider skipping the most symptomatic events for the individual in a training session or providing breaks.
- Simulated and real head movements should be limited during the VR training in sensitive individuals. Avoid the frequency range for angular and linear motions mentioned in the section above.
- Unexpected movements of the virtual self should be limited, and cues provided to aid user in their prediction of movements (e.g., visual leading indicators of the path, Earth-referenced ambient cues, virtual view of own nose) that may be symptomatic.

7.3.3 After Using VR Systems

- The limited evidence (Section 5.3.9.2) implies that 4 hours are typically sufficient to recover from cybersickness and that the most affected participants will be recovered by the next morning, even if in some simulator sickness cases some trainees had symptoms 6 hours later, and some cases have been observed 18 hours post-exposure; therefore, symptom decay should be tracked for future reference, and users experiencing symptoms should seek medical advice before resuming duties.

7.4 RECOMMENDATIONS ON DESIGNING VR SYSTEMS

(This paragraph is referred to Section 6.1.)

7.4.1 Recommendations on the Field of View and on Camera and Motion Control

- Dynamically restrict the FoV when the user moves rapidly. Where practical, use scene elements to naturally limit the FoV. A windowed environment, such as a cockpit, limits the viewer's FoV.
- Limit the linear and/or rotational speed (yaw) of the camera in order to reduce scene motion.
- Reduce scene movements producing visually perceived accelerations not corresponding to what would be expected during real body motion causing vestibular stimulation.
- Show visual leading indicators of the path to help the user to be prepared for upcoming changes of direction.
- Leave the viewpoint in full control of the user for initiating and terminating movement so that he/she is able to predict and to anticipate the upcoming visual feedback.
- Locomotion should be as similar as possible to natural, real locomotion both in terms of input (e.g., real user walking) and output (e.g., the camera swinging slightly up and down corresponding to the small amount of vertical body oscillation that is not ignored during user walking).

7.4.2 CG-Related Recommendations

- Be ready to downgrade the rendering quality at runtime to graphically simpler representations (reduce the scene realism).
- Implement user's own body perception since an increased sense of presence/embodiment could have a positive impact on reducing cybersickness.
- Imagery with depth cues that emulate real-world cues may reduce sickness.
- Consider blurring less significant areas of the image for the user task.
- Show rest-frame graphical cues in the foreground, or panorama elements in the background, as user-trusted elements for self-motion and orientation cueing.

7.4.3 Recommendations on Software Development

- VR developers in the Unity IDE® may wish to explore the usefulness of the GingerVR® toolbox, which incorporates a number of mitigation techniques "out-of-the-box" for assessment.

7.4.4 Recommendations Relating to Display Resolution

- VR frameworks should contain built-in resolution reduction techniques. Such an option is attractive because it requires no modifications to the simulation.

7.4.5 Recommendations to Reduce Screen Flicker

- Reduce display brightness.
- Maintain at least a 50 Hz refresh rate for large field of view and bright display.
- Avoid flicker and flashing on the edges of the display if a large FoV is employed.

7.4.6 Recommendations to Reduce Transport Delay and Considerations Relating to Display Pixel Lag

- Use manufacturer published values to select a display with low image processing times.
- For environments with rapidly changing imagery, more emphasis should be placed on selecting a display technology with fast pixel response times.
- Pixel response time and a display's refresh rate work in concert to display compelling imagery. Pixel response time, in the worst case, should meet or exceed the refresh rate interval for an optimal experience.

7.4.7 Recommendations Pertain to Display Refresh Rates and Simulation Frame Rates

- Frame rate should exceed the frequency of the display. This can be achieved in part by reducing the display resolution. Use a high refresh display and maintain a high, steady frame rate, especially for environments or applications where imagery changes rapidly.
- Due to frame rate render time variance, it is recommended that the frame rate render time be less than the refresh rate interval in at least 95% of frames with 99% being very desirable.
- For VR applications, a sustained frame rate of at least 90 frames per second is recommended.
- A low refresh rate promotes flicker. If a high frame rate (greater than 90 fps) cannot be maintained, seek other ways to reduce flicker.
- Reduced motion blur by increasing the frame rate.
- Avoid or design out the following: Asynchronous time warp, or similar techniques that pre-empt the graphics pipeline and insert extrapolated frames using the latest user pose data.

7.5 RECOMMENDATIONS IN REGARDS THE OPERATIONAL FACTORS

(This paragraph is referred to Section 5.3.)

- Node-based motion and viewpoint snapping may reduce sickness as compared to naturalistic continuous free movement.
- Real and simulated head movements around the 0.1 Hz range in the three angular axes, and around 0.2 Hz in the linear axis of motion should be avoided to reduce cybersickness.

- Visual flow should be provided on one axis (e.g., visual flow signaling smooth forward motion) to avoid cybersickness arising from visual flow information on multiple axes simultaneously (e.g., visual flow signaling smooth forward motion and left-to-right motion).
- Implied acceleration/deceleration in optic flow should be limited in order to mitigate cybersickness.
- Slow optic flow speeds should be used to reduce cybersickness, unless fast motion speeds are needed for training scenarios, in which case their durations should be limited.

7.6 RECOMMENDATIONS REGARDING THE ADOPTION OF TECHNOLOGIES/PRODUCTS THAT MAY INFORM OR REDUCE CYBERSICKNESS

(This paragraph is referred to in Section 6.3.)

It is important to disclose that the current Report is meant to provide scientific support for cybersickness mitigation in military training contexts for NATO allied nations and is in no way meant to endorse any products. (See also the Disclaimer statement in Section 1.4) Some of these products may hold promise in mitigating cybersickness but require further investigation. As such, below are suggestions for future research to evaluate the efficacy of such products:

- Products such as Otolith Labs' OtoBand BCV® device must undergo rigorous real-world military use case testing to validate if they can adequately prevent cybersickness.
- Products that integrate body sensors, eye trackers, and BCIs, which can give real-time updates on user health, mental workload, and cybersickness correlates must be rigorously tested and validated for their reliability and validity in providing relevant predictive cybersickness data.

7.7 REFERENCES

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Chapter 8 – CONCLUSIONS AND WAY AHEAD

Jelte Bos, Ben D. Lawson, Paolo Proietti, Ramy Kirollos[1]

8.1 CONCLUSIONS

The aim of NATO HFM-MSG-323 Human Factors and Medicine (HFM) and Modelling & Simulation Group (MSG) Specialist Team (ST) on "Guidelines for Mitigating Cybersickness in Virtual Reality Systems" was to collect all the best practice and design techniques and procedures that may reduce the occurrence of cybersickness by giving scientifically founded information on how to mitigate cybersickness with a focus on immersive virtual environments and VR goggles in particular, and as used in a defence setting in particular.

This was achieved by making reference to the literature on the topic, explaining the different findings related to cybersickness and the technology which elicits cybersickness, addressing cybersickness in terms of symptoms and how they can be measured, giving an overview of all factors known affecting cybersickness, both individual technological and operational, and providing an overview of not only scientifically proven, but also suggested (and unsupported) countermeasures, both from design, behavioral and neurophysiological points of view.

8.2 KNOWLEDGE GAPS

The interest on cybersickness topic is growing exponentially, due to increased use of VR equipment in general and head-mounted VR, and several issues related to VR also hold for Mixed and Augmented Reality systems which are partially addressed by the Study. An emerging research gap is that as AR and MR become a more widely endorsed military training and operations tool, investigations of cybersickness in AR and MR headsets will be necessary to understand the limitations, capabilities, and potential use cases of AR and MR headset technologies as well as VR headsets. A concern relates to the observation that the exponentially increasing interest on cybersickness also holds for the number of scientific papers published in the open literature, a relatively large proportion thereof, however, being reviews rather than studies on basic mechanisms or effectiveness of countermeasures. This already by itself asks for more research on these latter topics such that truly, i.e., both scientifically proven and understood, effective countermeasures can be provided.

As discussed above in the Report, cybersickness can formally be considered a form of simulator sickness. While simulator sickness is often related to the use of flight and driving simulators, which may be equipped with moving bases, cybersickness is generally related to the use of VR goggles. Due to an anticipated significant reduction of costs by using VR goggles on a moving platform in particular, and increasing dropout rates in simulators due do simulator sickness, cybersickness (then) is a topic which needs more investigation from that point of view as well.

Most literature addressing cybersickness uses relatively small sample sizes and takes into account one or two independent variables at a time. Small sample sizes in lab experiments investigating various individual differences on cybersickness susceptibility limit our ability to make inferences to a broader population. The fact that the symptom measures are not standardized across studies further limits inferences. While researchers will always prefer their own symptom questionnaire, having them all use an additional common questionnaire (the most established being the SSQ) would greatly advance the field.

[1] To cite: Bos, J.E., Lawson, B.D., Proietti, P., Kirollos R. (2021). Conclusions and Way Ahead. 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, Chapter 8.

Moreover, further research in the area of Behavioral and Neurophysiological cybersickness mitigation methods must be conducted to better investigate their side effects and long-term effects.

8.3 FUTURE STUDIES

The above gaps and some other findings in literature contribute to some recommended R&D activities and ideas to resolve cybersickness, some of which might be addressed in new studies within the NATO STO framework. To that end and based on the previous chapters, Table 8-1 elaborates on and extends a list of recommendations presented in Ref. [1], which report employed the phrase Extended Reality (XR) to encompass VR, AR, MR, and similar systems.

Table 8-1 lists the knowledge gaps and ensuing recommendations for future research. The priority of each gap is estimated (1 = highest), along with the urgency (Short, Medium, Long-term problem).

Table 8-1: Knowledge Gaps and Ensuing Recommendations for Future Research. (Table adapted from Ref. [1]).

Research Area	Action Item	Priority	Urgency	Remarks / Progress to Date
Basic Knowledge	Determine the various drivers of cybersickness and create a predictive model.	1	S	Models are in development concerning visual-vestibular conflicts, postural contributors, etc. These models could be divided into descriptive models (like that given in Ref. [2] holding for vertical (ship) motion), and functional (like the one proposed originally by Oman [3]), the latter preferably making use of well-established neurophysiological and control theoretical principles). These models could be built for the general psychophysiological susceptibility to XR influence and for current (pre-mission) state to predict a human sensorimotor and cognitive performance degradation, as well as appearance of the cybersickness symptoms.
	Distinguish visual-vestibular conflicts due to real self-motion and to virtual self-motion.	1	S	This distinction may make a big difference with respect to certain countermeasures. Increasing image fidelity may, e.g., decrease sickness with real self-motion, and increase sickness with virtual self-motion.
	Elaborate on visual factors.	1	S	Distinguishing, for example, angular from linear motion, frame effects from optic flow effects, and the multitude of depth cues (occlusion, stereo vision, motion parallax, etc.).

Research Area	Action Item	Priority	Urgency	Remarks / Progress to Date
Basic Knowledge (cont'd)	Study the overall time-course of cybersickness, e.g., for application in desensitization protocols.	1	S	Although it has been shown that (most) people do habituate (adapt) to virtual environments, it is not known whether, e.g., people initially showing a high susceptibility may suffer less than people who are initially less susceptible, but remain at a relative constant level of sickness. Even less is known of, e.g., mal de debarquement, retention, and adaptation.
	Elaborate on the effect of eye movements on cybersickness	1	S	Theories exist that oculomotor influences contribute to certain kinds of sickness. Further knowledge is required to design or optimize countermeasures employing (the suppression of) eye movements.
	Elaborate on the relationship between cybersickness and postural instability.	1	S	This could help to quantify aftereffects that could affect safe operation of apparatus and vehicles following on a VR training session. Links between vestibular migraine and postural instability have been observed.
	Establish means of determining user susceptibility to cybersickness and aftereffects.	2	S-M	Potential individual susceptibility predictors are being explored, such as past susceptibility, heritability, interpupillary distance, and postural control.
	Establish countermeasures to aftereffects.	2	M	Research continues on adaptation protocols, medications, behavioral ways to slow symptom progression (e.g., limiting head motion requirements), and technological countermeasures (e.g., Earth-referenced display cues.
	Establish human adaptation schemes in XR applications.	2	M	The time-course of adaptation is little studied apart from coarse details about single session and multi-session habituation.
	Identify factors that contribute to how provocative XR content is, and determine their relative weightings.	3	M	Some work has been done in this area, highlighting mismatched IPD, visual-vestibular mismatch, vergence-accommodation conflict, and other contributing factors.

Research Area	Action Item	Priority	Urgency	Remarks / Progress to Date
Basic Knowledge (cont'd)	Determine feasibility of testing an individual's visual dependency, including depth perception, and determine if such factors are associated with more severe cybersickness.	3	M	While depth cue sensitivity has been evaluated in the lab, eye tracking in the headset may make it feasible to integrate such a metric into XR applications and adapt content accordingly.
	Determine which sensory cues, beyond motion parallax, are sickness-inducing.	3	M	Work on sensitivity to motion parallax cues provides early indication of feasibility of evaluation at the sensory cue level.
	Determine specific training methods or exposure protocols required to drive sensory adaptation within XR systems.	3	M	Some evidence of the appropriate length of exposure and break schedules have been suggested, but these are preliminary at best.
	Determine aspects of sensorimotor processing /reweighting that are protective of cybersickness proclivity.	3	M	This research is in the early stages, with some evidence of its efficacy.
	Elaborate on the effectiveness of breathing techniques.	3	M	Although the effectiveness of controlled breathing has been shown, its mechanism is still not understood and optimization may be possible.
	Determine relationship between presence, cybersickness, and adverse physiological aftereffects.	4	M	Recent literature has revealed a highly intricate relationship between these factors, and a possible negative correlation between presence and cybersickness. More needs to be done on establishing the modulating effects of task parameters on these factors.
	Elaborate on the relationship between experience in different environments (e.g., that of high performance aircraft versus gaming) and susceptibility to cybersickness.	4	L	It is known that experienced pilots are more susceptible to simulator sickness, while younger pilots with ample gaming experience tend to suffer more form airsickness. This issue concerns habituation and relates to the (largely unknown) relationship between cybersickness and visual dependency as well. Knowledge about these issues seems to be helpful for selection and training.

Research Area	Action Item	Priority	Urgency	Remarks / Progress to Date
Evaluation	Standardize subjective and objective measurement cybersickness and its of aftereffects.	1	S	Too many symptom scales are used across labs and objective indicators lack specificity.
	Distinguish eyestrain due to accommodation-convergence conflicts from sickness due to visual-vestibular conflicts.	1	S	Currently, only the SSQ makes some difference in this respect, however without referring to the different causes.
	Develop an understanding of the magnitude of the cybersickness problem and its implications to job performance and career progression.	1	S	While individual differences in cybersickness have been widely documented, their implication to mass adoption of XR technology have not been carefully examined.
	Validate insufficiently proven effects of countermeasures.	1	S	Some countermeasures, either published in peer reviewed public papers or presented by the industry without public reports, may prove to be ineffective for a broader public or even be counter effective in unreckoned conditions.
	Establish product acceptance criteria and systems administration protocols to ensure that cybersickness and aftereffects are minimized.	2	S	Very few guidelines have been established for XR hardware.
	Develop automated solutions to track cybersickness symptom magnitude during XR exposure.	2	M	Real-time physiological data have been adopted in some labs but apart from sensitivity specificity must be known in addition.
	Establish XR content design guidelines that assist in mitigating cybersickness.	3	M	Experimentation is still common with respect to software for XR. Some guidelines have been offered by leading companies, but these are already beginning to fall out of date.

Research Area	Action Item	Priority	Urgency	Remarks / Progress to Date
Technology	Reduce visual latencies.	1	S	While end-to-end latency has been much improved due to advances in the tracking and rendering pipeline, visual latency persists and is generally (still) larger for MR applications such as video inclusions, than it is for mere virtual imageries.
	Create wide FoV HMDs that support task performance and presence but do not elicit cybersickness.	2	S	Increases in FoV are inevitable and may reduce or increase cybersickness, depending upon the improvement in symptoms obtained via greater presence versus worsening of symptoms with greater visual flow. Technology should incorporate effective countermeasures and optimal trade-offs between FoV, presence, and cybersickness.
	Integrate eye tracking into XR devices.	2	S	Eye tracking will allow user analytics for improved user experience and UI development, reduced workload, and improved graphical fidelity through foveated rendering, possibly reducing vergence-accommodation conflict and oculomotor discomfort, and allowing to implement dynamic focus strategies. See also about eye movements above.
	Allow for true variable focus, depending on the estimated vergence distance.	2	S	Some companies are already working on this. Note that local blurring does not replace true variable focus.
	Create peripheral devices for senses beyond vision and audition.	5	L	Sound fidelity has improved markedly and audio based on a head-related transfer function will be a crucial step. Consumer haptic/tactile devices are implemented in a basic sense but scope for improvement remains. Vestibular stimulation is in a very young but exciting stage of development, though still indefinite.
Medication	Test the effectiveness of new medications and delivery methods	2	S	For example, intranasal scopolamine has had a few successful trials, and Ondansetron is an effective anti-nausea drug according to some but not all reports.

8.4 SUGGESTED NEW TASK GROUP ACTIVITY

In order to better assess the impact of several individual characteristics, as well as the operational and technological ones, a Research Task Group (RTG) with an associated Cooperative Demonstrations of Technology (CDT) is suggested as HFM-MSG-323 follow on [4].

The advantage of this suggested RTG is manifold. First, the involvement of several NATO and EOP Nations in the Study will allow the implementation of a very large experimentation involving a wide target of participants spanning on age, sex, ethnicity, and different levels of familiarity with VR systems. Second, it facilitates standardization. Third, it will prevent duplication of research by a proper coordination. Forth, particular attention can be devoted to military personnel which has, or should have, different characteristics compared to the civilian population.

Furthermore, as VR headsets have captivated the interest of researchers, defence organizations and the consumer market are now showing a similar interest in AR and MR headset technologies. AR in particular has the potential to be used as an operational tool for warfighters in theatre as well as a training tool, potentially making it a very versatile tool. However, currently very little is known on cybersickness when using AR headsets. Research undertaken during the new proposed NATO RTG activity should therefore investigate cybersickness preponderance and characteristics when using AR (but also MR) headsets in order to effectively inform deployment of these systems for training and operational use cases across NATO militaries.

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Annex A – FULL REFERENCES LIST

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14. Abstract

The NATO HFM-MSG-323 Specialist Team (ST) addressed the best practice and design techniques and procedures that may reduce the incidence and severity of cybersickness by giving scientifically-founded information on how to mitigate cybersickness, with a focus on immersive virtual environments and virtual reality (VR) goggles as they are used in a defence setting. This has been achieved by making reference to the literature on the topic, explaining the different findings related to cybersickness and the technology which elicits cybersickness, addressing cybersickness in terms of symptoms and how they can be measured, giving an overview of all the individual, technological, and operational factors known to affect cybersickness, and providing an overview of scientifically proven countermeasures (and some noted as conjectural), from design, behavioural, and neurophysiological points of view.

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