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]

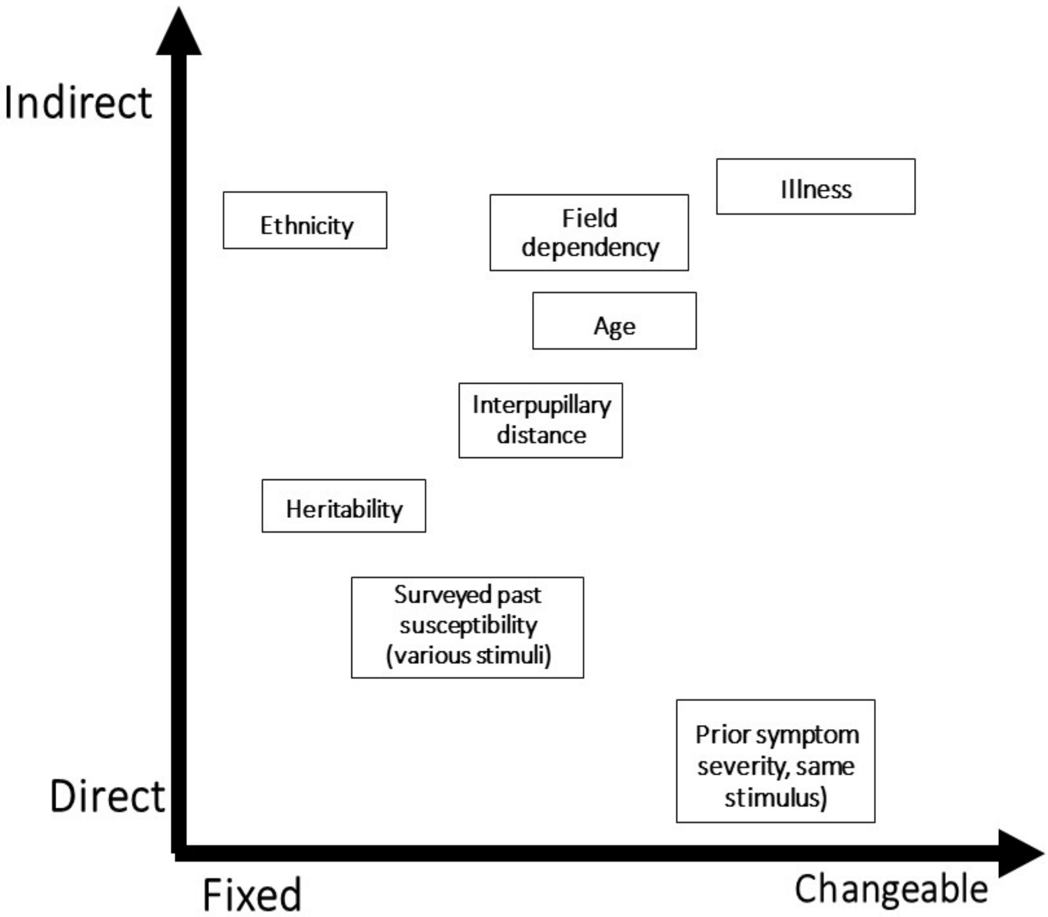

Figure 5-1: The Dimensions of User Characteristics.

[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

[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.

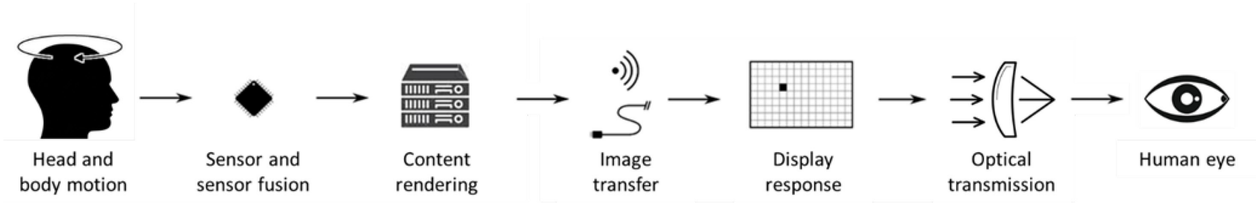

Figure 5-2: Motion-To-Photon Pipeline.

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.

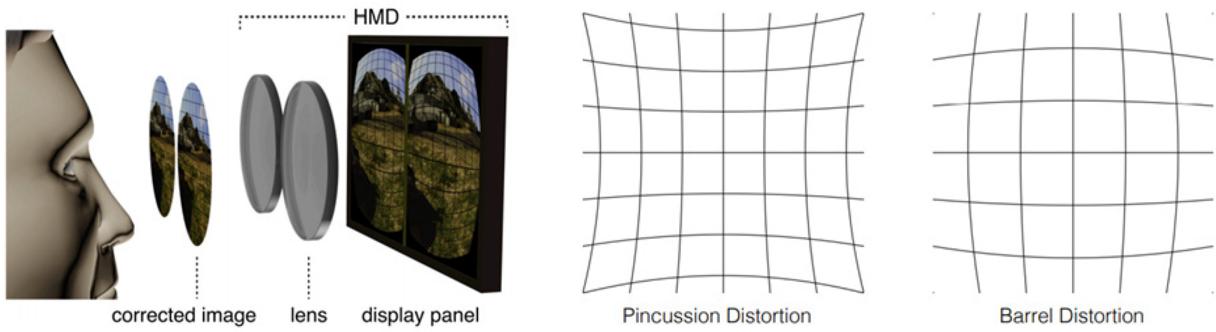

Figure 5-3: Image Aberrations.

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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