

CYBERSICKNESS PRIORITIZATION AND MODELING

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## ABSTRACT

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Motion sickness-like symptoms due to visual stimuli, or cybersickness, are a topic of significant public concern. From three-dimensional movies to new head mounted displays such as the Oculus Rift, the general public is being offered ever-increasing opportunities for immersive experiences. However, virtual environment opportunities are often accompanied with increased reports of “movie theatre sickness” and other cybersickness symptoms. Research in the field has posed over forty potential factors that affect cybersickness. The objective of this thesis is to prioritize cybersickness human factors and develop models to predict their effects. A thorough search of the literature is given, which summarizes the support, or lack thereof, for each factor. New experimentation is conducted for the factors with insufficient existing evidence. The factors with sufficient support were fitted to single-term models to use for guidelines and normalization. Cumulative models are then developed to predict individual and configuration level cybersickness effects.

The literature on certain factors is unclear due to selective reporting of configuration features, various configurations, different measurement methods, and limited studies. The literature regarding individual susceptibility to cybersickness is particularly limited. Therefore, experiments were performed that specifically addressed individual susceptibility with different display modalities. Common display methods such as head-mounted displays and screens were

examined. Stereoscopic effects were also examined due to recent renewed interest and unclear effects. All the experiments included surveys to collect data on individual susceptibility factors.

Cybersickness effects are not normally distributed, which decreases the reliability of common statistical measures on cybersickness data. A new statistical method for cybersickness research, called the zero-inflated model, is examined as an improved method for comparing the impact of the features involved in cybersickness. The zero-inflated model has the benefit of having a "non-susceptible" or "well" group built into the statistical test, which can be upwards of 50% of the participants in a study.

An analysis of the literature permitted several variables to be removed from further consideration and allowed single factor models to be created. Three independent variability models for individual susceptibility were found. The individual model explains 37% of the adjusted variance of a model and the linear models created for the hardware and software explain 55-70% of the adjusted variance. Since the variance as predicted by the models is not purely additive, the total explained variance with these models is likely 70-80%, which is a significant improvement over the models proposed by *Kolasinski's* that explain 34% of the variability of the model [1]. The models created using experimental results incorporating the individual, hardware and software had an average absolute residual accuracy of less than 1%.

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## KEY TO ABBREVIATIONS AND SYMBOLS

*AR* - Augmented reality

*R<sup>2</sup>* - Coefficient of determination or variance

*CAVE* - Computer Aided Virtual Environments

$$CPois(x, \lambda) = \frac{\lambda^x e^{-\lambda}}{\Gamma(x+1)}.$$

*DOF* - Degrees of Freedom

*FOV* - Field of view

*IVB* - Independent Visual Backgrounds

*MHQ* - Motion History Questionnaire

*MSSQ* - Motion Sickness Susceptibility Questionnaire

*Our HMD* - our experiment that compared a lightweight HMD to a heavy HMD

*Our Screen* - our experiment that compared a small screen to a large screen, but held the field of view and standing position constant

*Our Render* - our experiment that compared a monoscopic application to a stereo application

*SSQ-T/N/D/O* - Simulator Sickness Questionnaire, total, nausea score, disorientation, and oculomotor, respectively

*VE* - Virtual environment

*VR* - Virtual reality

*ZINB* - Zero Inflated Negative Binomial

\*\* Correlations =  $p < 0.01$

\* Correlations =  $p < 0.05$

· Correlations =  $p < 0.1$

$\lambda$  - lambda

$\Gamma(x)$  - the Gamma function

# 1 Introduction

Virtual and augmented reality technologies have been in development for decades. Throughout that period of time, a significant subset of users has suffered from motion sickness-like symptoms, which are commonly referred to as *cybersickness* or *simulator sickness*, depending on the setting. Virtual environments provide a generally safe setting in which to learn control systems, explore alternate realities, or consume media. Initially, these virtual systems were expensive to build and maintain and were predominately limited to military and research applications. Relatively recently, new systems have been created that are, or soon will be, available for purchase by general consumers. These systems include the Oculus Rift and Sony Morpheus projects as well as tracking equipment such as the Xbox Kinect and the Nintendo Wii. This technological realm, once predominately developed for the military, is opening up to the general consumer, which has brought attention to new applications as well as the human factors involved.

There are few empirically supported guidelines for cybersickness in virtual environments. The research for these guidelines was completed in three phases. The first phase involved an analysis of the literature to identify the possible factors of cybersickness and then model those factors. For example, a suggestion to decrease the size of the screen commonly appears in warning labels. The literature suggests that reducing the size of the screen to one half its size leads to an approximately 50% decrease in the severity and incidence of cybersickness symptoms. To aid future studies all source factors were labeled as *untested*, *unlikely*, *possible*, *probable*, *confirmed*, or *conflicted*. The second phase involved experimentation to clarify factors that were ambiguous or lacking in the literature. For example, with the exception of gender,

demographic studies were largely absent from the literature. Therefore, background surveys were utilized during this phase to collect demographic information. Experiments were approved by Michigan State University's institutional review board with the approval number 13-460.

The final phase involved the creation of cumulative models from multiple factors. There are many independent elements involved in virtual environments. A virtual environment can utilize a variety of displays, interaction techniques, rendering methods, and applications. To predict what will happen in a new system, several of these elements must be combined into one model.

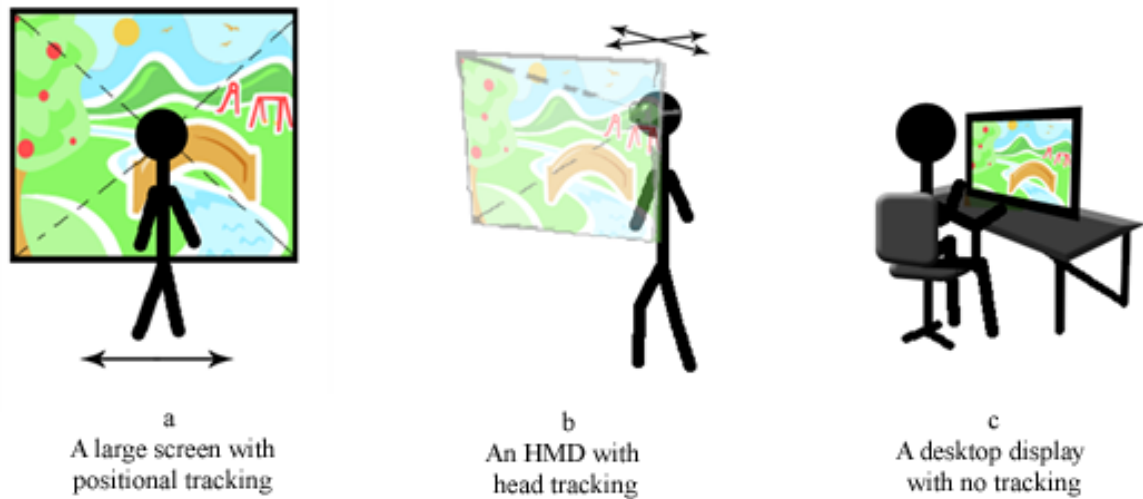
Cybersickness has been a known concern in virtual systems for decades, but the shift in its availability to the general public has renewed attention to the frequency of these issues. A quick Internet search for "movie sickness" returns thousands of results from people complaining of motion sickness after watching movies such as "The Hunger Games," "The Blair Witch Project," and others, particularly movies that were filmed in the 'shaky camera' style. In fact, "The Blair Witch Project" has been used as a cybersickness stimulus for research purposes. One particularly severe example of "movie sickness" is a movie that was shown to 294 seventh grade students wherein 36 students became ill enough to warrant hospital treatment [2]. Oculus Rift's best practices specifically mention cybersickness and offer suggestions on camera control to avoid inducing symptoms [3]. Nonetheless, cybersickness researchers report that incidences of cybersickness affect 30% [4] to 80% [5] of the general population. Given that virtual reality may cause disorientation, this is a safety issue as well as a usability issue. Despite

this high incidence of symptoms, the potential for cybersickness does not necessarily prevent individuals from using virtual systems [6]. However, it does signify that improved methods to minimize the impact of cybersickness are of critical importance.

## **1.1 Cybersickness Factors**

Despite that fact that cybersickness has been a known issue for decades, its general theoretical foundations are fundamentally incomplete. There are very few guidelines on the use of virtual systems and the durations of safe exposure to them. Television and game manufacturers place warnings on their devices suggesting limited usage, but the suggested durations are vague and are typically not based on empirical or theoretical evidence [7,8]. One reason for the difficulty in identifying the factors of cybersickness is the large number of potential factors of cybersickness.

*Kolasinski* presented over 40 possible cybersickness factors in 1995 [9]. Examples of such factors include screen size, stereoscopic rendering, the tasks performed, gender, mental rotation ability, and interaction paradigms. These factors were grouped into three sources: simulator, task, and individual factors. Moreover, there are many possible system configurations and many of the factors can be selected independently of each other. For example, a new virtual environment may allow a user to choose from a head-mounted display or a large screen, monoscopic or stereoscopic rendering, a joystick or mouse for movement, and the ability to track participant rotation only or to track position as well. This results in an exponential number of configurations. For example, Figure 1 shows three different ways that an identical scene may be presented, with or without tracking to update the virtual view.



**Figure 1: Common Implementations of Virtual Environments**

Given the numerous factors and various installations, it is sometimes difficult to determine if any given cybersickness effect is due to the system configuration or the factor under consideration. Another impediment is that cybersickness is highly individualized in nature. One participant may be very sensitive to visual stimuli, whereas the next participant may show little or no sensitivity to the same stimuli. Cybersickness in one participant may induce eye strain and headaches, while for another participant it may induce balance and nausea symptoms. Since the effects are individualized, the experimental design of cybersickness studies could benefit from studying the same participants for each condition. This is difficult to accomplish because a participant's symptom incidence and severity tends to decrease with each session. Participants are also frequently hesitant about additional time requirements. Currently, the decrease in symptoms and the difference between participants are ignored as there are no models available to normalize these effects. Phase one and three of our cybersickness research directly addressed these problems by creating models to normalize some of these effects.



Prior general predictive measures of cybersickness have been suggested by *Kolasinski* [1] and *So* [10]. *Simon* [11,12,13], and *Jones, Kennedy, and Stanney* [14] have suggested research programs that would ultimately lead to the creation of predictive models, but these research programs have not been realized. *Kolasinski's* model is the only model that accounts for the individual. *Kolasinski* proposed a testing/qualification procedure and a predictive linear model based on testing results, but the procedures could not be completed outside an academic setting since it required special equipment which requires several square feet of room. This is a problematic issue as it prevents the results from providing guidance unless users can visit a lab to be tested. *So's* cybersickness dose method, which only considers the visuals of a scene explained 85-97% of the proportion of variability the model, or coefficient of determination. While this seems to have good accuracy, their experimentation only included six points and small data sets are highly prone to over fitting which results in higher coefficients of determination than what would occur in practice. This model also assumes no interaction with the system so the result can only be partially applied to the dynamic systems of general virtual environments. In addition, the measure requires an application to be built before a prediction can be made, which makes the measure difficult to apply during the application design stage. A later study by *So, Ho, and Lo* expressed their reservation regarding the effectiveness of a cybersickness dose value when they found that scene complexity did not significantly affect the level of cybersickness [15]. *Simon* and *Jones, Kennedy, and Stanney* both suggest using the results of every tested configuration and then adjusting the predicted results according to how the configurations differ. *Simon* suggests doing this directly with large linear models that include all the factors, while *Jones, Kennedy, and Stanney* suggest using the average effect of

each factor and adjusting the results accordingly. *Simon and Jones, Kennedy, and Stanney* require a large number of configurations be tested as well as a uniform distribution of configurations. It is difficult for cybersickness research projects to meet these requirements and the literature does not provide the data to create the models used in their approach.

## **1.2 Contributions of this Thesis**

This thesis presents an analysis of the factors that influence cybersickness symptomology, new predictive models for individual and novel configurations, and new statistical methods for analyzing the data acquired during cybersickness research. The primary results of the research were:

- Several factors, such as display type, are shown to have negligible effects and those effects can be explained by other factors.
- Some factors were found to be too general and were consequently broken into sub-factors. For example, ‘field of view’ can refer to the size of the real screen or the ratio of the real screen to the virtual rendering plane. Also, researchers have only studied the ‘field of view’ measure along the diagonal or horizontally across the screen. The effect of increasing the size of the screen vertically is unknown.
- An analysis of individual factors resulted in several guidelines that can help to reduce the incidence of symptoms, such as decreasing the size of the screen and seating participants.
- Three susceptibility factors that correlated with cybersickness were found, and these factors are shown to be independent of each other. These factors are a history of

motion sickness, a history of headaches, and history of video game play of genres known for large amounts of forward motion.

- Models created to predict individual differences can be used to normalize the results of different participants, allowing for the inclusion of different participants in each condition.
- The model that was created for individual susceptibility explains 37% of the adjusted variance.
- The linear models that were created from the literature results incorporating hardware and software factors explain 55-70% of the adjusted variance.
- The model that was created from experimental results incorporating individual, hardware, and software factors has an average absolute residuals of less than 1%.

Because coefficients of determination are not purely additive, the total adjusted variance explained is likely 70-80%, which is a significant improvement over *Kolasinski's* 34% of total variance. Since different statistical models were used for the experimental and literature results, these models could not be directly compared.

Using the results of this thesis, virtual environments can be dynamically adapted to participants. The single factor models allow developers to create low, medium, and high cybersickness probability settings, trading features for decreased susceptibility. For example, a high field of view provides greater immersion, but also produces a higher probability of cybersickness. Using the field of view model, participants can estimate how much they need to

restrict the display to reach a certain symptom level for the "low" setting. The individual susceptibility model can be applied prior to entering a virtual environment, so developers can suggest initial settings for the user.

## 2 Background

Research on cybersickness and simulator sickness has been ongoing for several decades. The original objective of the studies was to determine the factors that were most likely to make trainees ill in military simulators. As a result, the research prior to 1995 focused on hardware with the belief that improving the hardware would eliminate the problem. This theory began to be challenged in 1995 by *Mon-Williams, Wann, and Rushton* who suggested that improving the screen hardware may actually increase symptoms [16]. The change in systems from simulators with mock ups of controls to visor and large screen displays made the systems more conventional. Unfortunately, reports of cybersickness began to increase. The change in systems also resulted in new terms for the symptoms including *cybersickness*, *visually induced motion sickness* (VIMS), *virtual reality induced symptoms and effects* (VRISE), and others. The distinction between *cybersickness* and *simulator sickness* is that simulator sickness implies a physical mockup of the control systems while cybersickness lacks such a mockup. In “Cybersickness is not Simulator Sickness”, *Stanney, Kennedy, and Drexler* proposed that cybersickness and simulator sickness are different maladaptations [17]. *Stanney, Kennedy, and Drexler* reported that the symptom profile, or the relative severity of oculomotor, disorientation, and nausea symptoms, differed between simulator and non-simulator systems, as shown in Table I.

More recently, there has been a call to formally unify the two fields by *Blea et al.* [18], *Bos, Bles, and Groen* [19], and *Smart, Otten, and Stoffregen* [20]. They claim that all the symptoms are due to the same source, namely *postural instability*. Postural instability is the extent to which a

person sways when standing still. Whether these two fields will reunite is uncertain, but simulator sickness is currently considered to be the ancestor of cybersickness research.

**Table I: Related Conditions Symptom Profiles**

|                       | <i>Military Simulators</i> | <i>Sea Sickness</i> | <i>Space Sickness</i> | <i>Cybersickness</i> |
|-----------------------|----------------------------|---------------------|-----------------------|----------------------|
| <i>Highest Rating</i> | Oculomotor                 | Nauseagenic         | Nauseagenic           | Disorientation       |
| <i>Middle Rating</i>  | Nauseagenic                | Oculomotor          | Disorientation        | Nauseagenic          |
| <i>Lowest Rating</i>  | Disorientation             | Disorientation      | Oculomotor            | Oculomotor           |

Although research in cybersickness and simulator sickness has been ongoing for decades, there are few fundamental theories about them. This is partially due to the large number of potential factors involved in cybersickness and simulator sickness. Moreover, many of the hardware and software factors such as display type, stereoscopic rendering, and navigation can be selected independently of each other. This results in an exponential number of potential configurations to test.

Exacerbating these issues is the fact that there is currently no standard testing system. The virtual environment performance assessment battery (VEPAB), which was designed for simulator performance and usability, was developed in 1994, but has not been widely used [21]. The tasks in the VEPAB focus on the quality of visuals, locomotion, tracking, object manipulation, and reaction time in virtual environments. There are 22 tasks in total, including distance and height estimation, navigation tasks, and simple activation of controls. The virtual environment used by the VEPAB was eventually deemed to be overly simplistic due to later hardware and graphics improvements, but no replacement system has been developed. While

the original VEPAB environment is no longer in use, the variety of required activities/tasks it used still applies to today's virtual environment interfaces.

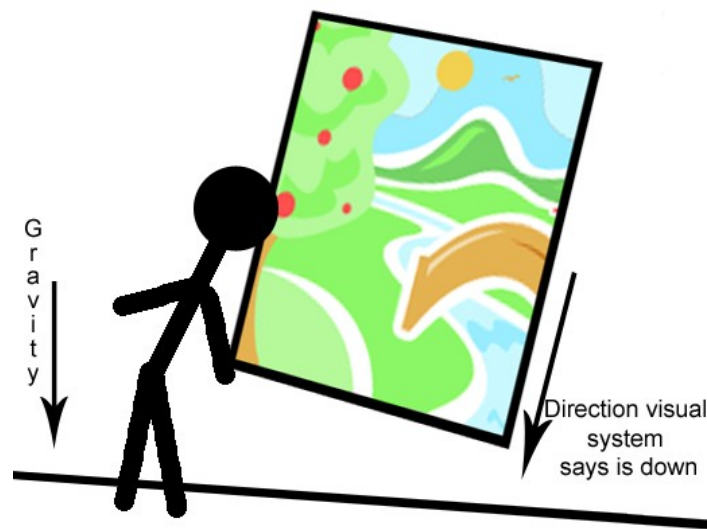
## **2.1 Definition of cybersickness**

Cybersickness is defined as the feeling of symptoms similar to or related to motion sickness in a virtual environment. Since there is typically no actual physical motion, cybersickness is generally considered to be "visually induced." Medically, cybersickness symptoms may include nausea, pale skin, cold sweats, vomiting, dizziness, headache, increased salivation, and fatigue [22]. Because virtual environments place additional strain on the eye, the symptoms can also include difficulty focusing and eyestrain [17]. Because cybersickness is polysymptomatic (many symptoms) and polygenic (manifested symptoms differ from individual to individual), the degree and sensitivity to the environment varies widely between individuals. When cybersickness is said to increase, it typically means that its severity and incidence frequency has increased.

The greatest risks in virtual systems are disorientation and nausea. Virtual systems can affect eye function and diminish distance perception, and can therefore create a travel risk after using them. Emetic responses are uncommon, with less than 2% of participants experiencing nausea or vomiting, but it is known to be the least tolerated symptom [23,24,25]. More worrisome is the fact that it may take time for the effects induced by virtual systems to subside. Studies by *Stanney and Kennedy* [23] and *Stanney et al.* [24] demonstrate that the nausea caused by virtual environments may persist for an hour and that disorientation may last for two to four hours.

## 2.2 Theories

Cybersickness researchers rely on a variety of theories on the cause of illness to design and support their experiments. The biological causes of cybersickness have not been firmly established, and different theories hypothesize the existence of different responsible factors in virtual environments. The most prevalent theories in cybersickness research are *sensory mismatch*, *postural instability*, and *rest frame theory* [18,19,26,27,28].



**Figure 2: Orientation Conflicts with Incorrect Visual Stimuli**

Sensory mismatch is the most common theory. It posits that if the stimulus from the outside environment is perceived differently by different senses, it will induce motion sickness. For example, if a picture is tilted as shown in Figure 2, the vestibular system of the participant experiences gravity as acting straight down, but the visual system perceives that gravity should be tilted with the picture. Sensory mismatch is often the explanation as to whyvection, the perception of the world moving away from the user, is strongly correlated with feelings of



cybersickness. The features of primary concern in sensory mismatch theory are accurate tracking and navigation.

Postural instability theory posits that motion sickness will be induced if a person is unable to maintain a stable posture given a stimulus from the outside environment. The stability of a posture is typically defined as the amount of sway in the posture. Using the picture example, the individual's posture may be slanted to correct for the orientation of the visual stimulus, but because gravity is felt straight down, this posture becomes unbalanced. The more unbalanced the posture becomes, the more ill the participant feels. Postural instability is not as straightforward as having sway versus no sway. Seating participants, which should eliminate sway, does decrease illness but does not completely remove the effect [29,30]. In addition, well participants often have more sway along certain axes than sick participants [31]. Postural instability can be viewed as a more restricted form of sensory mismatch, because it focuses on the vestibular system being unable to cope with a stimulus. Postural instability theory is gaining popularity in the cybersickness research community because it is subject to objective evaluation.

Rest frame theory is based on the direction the user perceives or assumes is “up” in relation to the world. Theoretically, the degree of symptoms relates to how much this perception deviates from actual gravity. It is similar to postural stability in that the symptoms are due to a perceived "up" versus actual gravity. However, it is more general to when postural control may be less of a factor, such as when participants are seated. Rest frame theory largely relies on the eye's vestibulo-ocular reflex (VOR), or the eye's ability to track objects when the head is moving. *Virre*

explains that the body assumes a certain proportional gain between the vestibular and visual systems within certain frequencies of movement [27]. If the gain of the VOR changes (such as when a prescription in eyeglasses changes), the habitual level of movement is no longer accurate, and the eyes must re-adapt until the objects are stabilized given the new VOR gain (typically a few days for a 5% prescription change). *Virre* also mentions that two states of VOR can exist and that the nervous system can quickly switch between these two states. The theory is frequently used to explain why the frequent use of a virtual environment results in less cybersickness and is the basis for the use of independent visual backgrounds [32]. There is some argument against the two state VOR theory from *Kennedy and Stanney*, who mention that the altered VOR persisted between their experimental sessions rather than simply switching when the immersion began [33].

### **2.3 Cybersickness Detection**

Cybersickness researchers have diverse means to determine the severity and incidence of participants' symptoms. The most commonly used measures are questionnaires, with the simulator sickness questionnaire (SSQ) from *Kennedy et al.* being the *de facto* standard [34]. The SSQ does not readily permit the monitoring of symptoms as it takes too long to administer. Thus, one-question scales that ask for a participant's current state are regularly used. Given that questionnaires are subjective, objective measurements using postural instability and physiological state are also under development. Postural instability is gaining popularity as inexpensive and robust sensors become available. The physiological state measure has only been studied in the last several years and is currently not reliable enough to replace other methods of measurement.

### 2.3.1 Questionnaires

The most common questionnaire in cybersickness studies is the simulator sickness questionnaire (SSQ), which was developed in 1993 by *Kennedy et al.* [34]. The questionnaire and its scoring metrics are included in Appendix A. It remains the most commonly applied measure in cybersickness research and is frequently used as the target value during the development of new detection measures. The SSQ consists of 16 questions requesting the current degree of severity of each symptom. The severity scale is “none, slight, moderate, or severe” or “0, 1, 2, 3”, respectively. The participants’ responses are grouped into three categories, each with its own weighting. A score below 10 is traditionally considered to be normal. The three categories are nausea, oculomotor, and disorientation, and are abbreviated N, O, and D, respectively.

The SSQ does have some notable disadvantages. There is a degree of cross-correlation in the categories. For example “general discomfort” appears in both the nausea and oculomotor categories, and there has been some concern over its generalization because it was developed based on a military demographic. *Bouchard, Robillard, and Renaud* refer to this redundancy in the categories as *loading*. They attempted to remedy both issues by refactoring the SSQ using a nonmilitary populace to avoid cross-loading and created a new questionnaire with two categories: nausea and oculomotor [35]. The participants consisted of 71% females, a third of whom had anxiety disorders. This demographic is dissimilar from the general populace as well as the populations reported in most nonmilitary cybersickness studies, and the usage of the refactored SSQ is limited.

Following the SSQ in popularity are numerous verbal one-question surveys that analyze symptom severity over time. One-question scales vary from study to study, but typically involve asking the participants to report their current level of discomfort as a single number at regular intervals. The disadvantage of these scales is that they disturb the participants on a regular basis and increase their awareness of their physical state. This results in “priming” or “demand” characteristics, or an increase in reported symptom due to expecting the symptom. There has been little research on the level of this effect in cybersickness, but there is potentially a strong effect. *Young, Adelstein, and Ellis* tested the effect of demand characteristics on the SSQ by considering post-immersion scores with and without a pre-immersion test [36]. Not surprisingly, the scores on the post-test were higher when a pre-test was given. In their results, the nausea category had the largest priming effect with a change of symptoms resulting in the post-test scores being only a third as high without the pretest. A related study by *Nichols et al.* analyzed the correlation of the participant’s sense of the presence of an “interface” and its effect on cybersickness, where the “interface” was defined as: “...whether the interaction devices or display quality interfered with the virtual experience, and how well participants felt they could concentrate on the tasks in the virtual environment [6].” They found negative correlations between the “interface” and all the SSQ categories, but they also found no correlation between enjoyment and sickness ratings, signifying that feeling ill did not stop the participant from enjoying the experience. This suggests that if participants are sufficiently distracted, they may not notice mild symptoms.

*Ling et al.* reported the opposite finding in a sense [37]. They found a positive correlation between participants that were more likely to get involved with their virtual environments and cybersickness.

### **2.3.2 Postural Instability**

Given the subjective nature of questionnaires, there have been several attempts to develop objective measurements for motion sickness over the past two decades. Postural instability was posed as a low-cost objective measure that caused limited interference with the participant and could yield continuous symptom levels. Postural instability detection relies on the postural instability theory of motion sickness, which states that the more ill someone becomes, the more unstable their posture becomes. In practice, postural instability detection is neither continuous nor does it leave the participant undisturbed. Postural instability detection typically requires that a specific standardized stance be taken every few minutes, resulting in greater interference than one-question scales, and only the position data recorded during the stance is used for analysis. Postural instability researchers initially had difficulty finding consistent correlations with cybersickness scores. The postural instability stances were then monitored for "stance breaks" or "time-till-failure." Stance breaks occur when a participant can no longer maintain a stance and is typically recorded as the number of breaks required per minute. Time-till-failure is the amount of time between when the participant first enters a stance to when a break occurs. As *Cobb* explains, there are several flaws with these methods [38]. *Cobb* found that many of the definitions of stance breaks were sufficiently vague, and that the same description could yield different results. For example, "loss of balance" could mean that the foot moved from its original position by any measurable amount, the foot moved more than

two centimeters from the original position, or several other movements. In addition, since the results generally rely on special postures, there is a potential for learning effects.

*Kennedy and Stanney [33]* bridged postural stance and sway by examining sixteen different stances with the intent of identifying a stance that is sensitive to postural instability. After determining a stance (the tandem Romberg stance, which is comprises of a heel to toe position of the feet, arms folded across the chest, and eyes closed), they analyzed the correlations amongst time-till-failure, extent of head movement, level of movement as described by an observer, and horizontal velocity mean and standard deviation. They found the most reliable result with the horizontal velocity mean. The correlation of the horizontal velocity mean with illness was preliminary, but promising.

With the development of robust postural sway hardware, postural stability measurement studies gained reliability and accuracy. Both *Cobb* and *Regan* examined postural sway in their studies and reported correlations with cybersickness. The primary disadvantages of postural sway methods continue to be that a specific stance is often required that disturb the participant, the specific stance may result in a learning effect, and the analysis is sensitive to the sampling procedure used. This means that an analysis may not be applicable to different stances, sampling periods, or sensor positions. For example, *Ehrlich* showed no effect on postural sway while their SSQ scores showed an increase in symptoms with a sampling period of 0.54 seconds [39], while researchers that have found correlations employed far smaller sampling periods, for example, *Chang et al. [40]* used a 40 Hz rate, *Smart, Otten, and Stoffregen [20]* used a 40-50 Hz rate, and *Villard et al. [31]* used a 60 HZ rate. For these reasons, while

postural stability has shown good correlations with cybersickness, it does not yet have a reliable predictive method (although *Smart, Otten, and Stoffregen* discuss the use of potential discriminate functions).

### **2.3.3 Biometrics and Physiological State**

To address the fact that postural instability interferes with virtual environment interactions and has the potential for learning effects, there have been attempts to develop objective detection measurements that do not disturb the participant. In recent years, there has been an exploration of “bio-signals” or “physiological signals” measurement of cybersickness. Physiological signals such as the heart rate (known as the R-R interval) and blood pressure are analyzed to determine their correlations with cybersickness. This method has the advantage of having a very limited interference with the participant's usage of the virtual environment and a lower potential for learning effects than that of postural instability methods. The disadvantages of the method are that wearing the sensors is often uncomfortable and determining the correlations with cybersickness is challenging. Some of the more common detection sensors include electrocardiogram (ECG), blood pressure, electrogastrogram (EGG), and respiration (RSP). ECG monitors the heart signal and EGG monitors stomach movement. Two methods have shown promise thus far: ECG/blood pressure ratios and the EGG power spectrum. *Roberts and Gallimore* attempted to use the EGG as an exclusive detection measurement in 2005 [41]. They analyzed EGG data for gastric shifts, magnitude changes, and power spectrum changes. They focused their attention on tachygastria (an EGG with a power spectrum of four-nine cycles per minute rather than the standard three cycles per minute). They found that tachygastria was present during participants’ exposure to stimuli and that it

was correlated with duration. They developed a neural network that used the EGG signal as the input and the questionnaire rating as the target for each individual, which converged to attain a sum-squared error of less than one. The development of a general model was not discussed.

A list of the sensors used in cybersickness research is presented in Table II.

**Table II: Physiological Sensors Used in Cybersickness Research**

| <i>Sensor</i>                | <i>Definition</i>                                                                 | <i>Correspondence to Cybersickness</i>                                     |
|------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Blood pressure               | Standard blood pressure measurement                                               | Indirectly related to heart rate                                           |
| Electrocardiogram (ECG)      | Detects the heart rate (R-R interval)                                             | The ratio of low to high frequency power has shown a correlation           |
| Electroencephalogram (EEG)   | Detects brain activity                                                            | Preliminary results only                                                   |
| Electrogastrogram (EGG)      | Detects stomach movement and strength                                             | The magnitude and high power frequencies have shown a correlation          |
| Electrooculogram (EOG)       | Detects the movement of the eye                                                   | None                                                                       |
| Galvanic Skin Response (GSR) | Detects the amount of moisture produced by the skin. It is associated with stress | None                                                                       |
| Respiration (RSP)            | Strength and frequency of breath                                                  | The magnitude and high power frequencies have shown a possible correlation |

Also in 2005, *Kim et al.* examined a majority of the common physiological signals for any correlations with cybersickness using a highly provocative stimulus (78.9% of the participants experienced symptoms after only 9.5 minutes) [5]. They found a correlation between cybersickness and EGG data, eye blink rate, and heart rate. The EGG displayed a gastric



tachyarrhythmia (a higher than normal spectral power) increase during the duration of the exposure to the stimulus. The eye blink rate decreased at the beginning of the exposure period, increased beyond the baseline within several minutes, and then leveled. The heart rate was faster at the beginning and then slowly decreased down to the baseline, but returned quickly to the baseline when the participant exited the virtual environment. Of these effects, EGG is the signal that is most highly associated with cybersickness. The heart rate and eye blink rate can be explained by the psychological effects of the participant's initial interest in the new environment and the process of becoming familiar with it.

The power frequencies of the physiological signals are often split into a lower frequency range (LF), approximately 0.04–0.15 Hz, and a high frequency range (HF), 0.16–0.45 Hz. *Kiryu et al.* examined ECG data, blood pressure, and respiration [42]. They reported a correlation between duration and cybersickness using ECG, blood pressure, and respiration LF/HF ratios as measurements [42]. *Watanabe and Ujike* also found that the LF/HF ratio obtained from the heart-rate correlated with duration [43]. While the LF/HF ratio did not display a significant correlation with the travel conditions in their experiment, the SSQ did display a significant correlation. Because the LF/HF ratio between the two conditions was consistently different, the LF/HF may not be as sensitive as the SSQ, but it is promising and warrants further analysis. The underlying assumption of these studies is that a large LF/HF ratio occurs when the sympathetic nervous system is very active. Biologically, this means that the heartbeat becomes stronger and/or the blood flow has decreased turbulence.

The pupillary reflex (how much the pupil dilates compared with a participant's baseline) has a possible but poorly understood correlation with cybersickness [44]. *Harvey and Howarth* found that skin temperature did not have a correlation with cybersickness [45]. The correlation of EEGs with cybersickness have been more difficult to determine, but *Ji et al.* have proposed the potential neural pathways that might be affected [46]. *Chang et al.* also examined to the correlation between EEG data and cybersickness [47]. They found that lower delta and theta powers were associated with fewer symptoms whereas higher alpha and beta powers were associated with fewer symptoms. The usefulness of EEG data for the real time prediction of cybersickness remains undetermined.

## **2.4 Factors**

One major issue in cybersickness research is the number of factors and the flexibility of their configurations. In 1995, *Kolasinski* listed over 40 possible factors [9], and *Renkewitz and Alexander* updated this list in 2007 [48]. The combined list is shown in Table III. This large number of factors necessitates the prioritization of experiments. In early simulator sickness research, the studies focused on hardware, with the belief that hardware advances would resolve the issue. However, although several of the hardware factors have improved significantly over time, reports of cybersickness have actually increased. Research later shifted with some success to focus on navigation direction and rotations.

Unfortunately, comparing results from different researchers and their labs has proven to be difficult. The navigation paradigms, rendering parameters, and displays can generally be selected independently of each other. The result is uncertainty as to whether the variance in the results from different researchers is due to the factors being studied or the differences in

the configurations being used. For example, when examining the effect of field of view, *van Emmerik, de Vries, and Bos* [49] argued that their results differed from those of *Draper et al.* [50] as a result of screen size differences. *Peli* [51] argues that they found lower symptoms than *Howarth and Costello* [52] when examining monoscopic versus stereoscopic viewing due to their dissimilar survey procedures and a more active task.

## **2.5 Cybersickness Models**

A general predictive model for cybersickness is currently lacking as each factor is independently considered for a given configuration. This means that for each new configuration or application, the only method to ascertain its expected cybersickness effects involves testing it with participants. While there are no general models in use, experimental programs and theoretical models have been proposed.

In the 1970's and 1980's, *Simon* proposed the empirical testing of several factors using a central-composite experimental design, which is a factorial design that includes median and median leave-one out experimental runs [11,12,13]. Median and median leave-one-out experimental design is similar to mean and mean leave-one-out experimental design, but uses the median rather than the mean as the primary statistic to compare results. The conditions either include all the factors or leave one factor out. The relative magnitude of each effect is then determined by regression analysis. Using these magnitudes, cybersickness could theoretically be modeled and held below a specific threshold.

The *Jones, Kennedy, and Stanney* protocol proposed in 2004 modified *Simon's* approach [14]. Rather than creating a parameterized model of cybersickness, they proposed to extrapolate

new data using previous tests. *Jones, Kennedy, and Stanney* and *Simon* both considered the configuration as a whole, but ignored individual factors.

**Table III: Potential Factors in Cybersickness**

| <i><b>Individual</b></i>               | <i><b>Simulator (Display System)</b></i> | <i><b>Task</b></i>                        |
|----------------------------------------|------------------------------------------|-------------------------------------------|
| Age                                    | Binocular view                           | Altitude above terrain                    |
| Concentration level                    | Calibration                              | Degree of control                         |
| Ethnicity                              | Color                                    | Duration                                  |
| Experience with real-world task        | Contrast                                 | Global visual flow                        |
| Experience with simulator (habitation) | Field of View                            | Head movements                            |
| Flicker fusion frequency threshold     | Flicker                                  | Screen luminance                          |
| Gender                                 | Inter-pupillary distance                 | Method of movement                        |
| Illness and personal characteristics   | Motion platform                          | Rate of linear or rotational acceleration |
| Mental rotation ability                | Phosphor lag                             | Self-movement speed                       |
| Perceptual style                       | Position tracking error                  | Sitting versus standing                   |
| Postural stability                     | Refresh rate                             | Type of application                       |
| Eye dominance                          | Resolution                               | Unusual maneuvers                         |
|                                        | Scene content (scene complexity)         | Vection                                   |
|                                        | Time lag                                 |                                           |
|                                        | Update rate                              |                                           |
|                                        | View region                              |                                           |
|                                        | Ambient brightness                       |                                           |
|                                        | Screen distance to the eye               |                                           |
|                                        | Type of haptic feedback                  |                                           |
|                                        | Ambient temperature                      |                                           |
|                                        | Olfactory feedback                       |                                           |
|                                        | Audio feedback                           |                                           |
|                                        | Tracking method                          |                                           |

So attempted to model cybersickness with the *cybersickness dose value* [10], which is modeled after the Motion (sea) Sickness Dose Value (MSDV), which can predict sea sickness in passengers. The basis of the metric is how much a scene changes over time along the vertical,

horizontal, and radial axes multiplied by display, task, and individual scaling factors. An update on the progress of this “spatial velocity” or “cybersickness dose value” was provided in 2002 by *Chen, Yuen, and So* [53]. This publication removed the display, task, and individual scaling factors. A later study by *So, Ho, and Lo* expressed doubt on the sole use of their cybersickness dose value when it was discovered that scene complexity did not significantly affect the level of cybersickness. Because high scene complexity undoubtedly affects the cybersickness dose value, additional factors in the scene must be considered [15].

One problem with all of the above models is that susceptibility is not addressed. Prior studies have shown that single individual attributes can explain 10-18% of the variance in an experiment and that several individual attributes may explain nearly half of the variance [23,54]. The *Simon and Jones, Kennedy, and Stanney* experimental protocols require a large number of empirical results, the consideration and reporting of several factors, and a uniform spacing of data points. Cybersickness research is rarely able to meet such stringent requirements.

*Kolasinki* proposed a linear model that explained 34% of the variance in an experiment. As *Kolasinki* explains, cybersickness data is not normally distributed, which makes linear models less reliable. In addition, certain factors, such as perceptual style, are time consuming to perform and cannot be tested at home. This makes these factors unsuitable for commercial products.

### 3 Analysis of Factors

A cybersickness model with over 40 factors would be difficult to understand and would be highly prone to over fitting given the limited number of data points. Therefore, eliminating the unlikely factors is critical for making the cybersickness modeling problem tractable. Using the literature, we sought to find support, or the lack thereof, for the factors posed by *Kolasinski* [9] and *Renkewitz and Alexander* [48]. The factors were rearranged into three categories: hardware, software, and individual, as shown in Table IV.

The factors were further assigned to subcategories for ease of reference and to delineate features that may be correlated with each other. Several factors were added to the list. These include susceptibility features such as vision correction and video game play as well as new topics in cybersickness such as independent visual backgrounds. These features are marked with an (A).

Rendering parameters such as field of view were placed in the hardware category, although software may affect them as well. While rendering parameters may be affected by software, they are typically limited by hardware. The analysis of individual factors is more tentative, as individual factors are often based on potentially inaccurate studies of motion sickness, as shown in the age studies by *Arns and Cern* [55] and *Park et al.* [56].

Several features that were immediately removed from consideration are shown in Table V. These features were ambiguous, near duplicates, or no longer applicable due to hardware improvements. Some may argue that flicker fusion and phosphor lag remain applicable. However, the displays that show noticeable flicker are usually deemed unfit for virtual reality

and have already been removed from use, and phosphor lag is directly related to blur because a lengthy phosphor lag leads to visual blur with eye movements. “View region” was renamed to "focus area" to include both the location of the screen and the locations of the objects within the screen.

**Table IV: Re-categorized Potential Factors in Cybersickness**

| <i><b>Individual</b></i>                | <i><b>Hardware</b></i>                | <i><b>Software</b></i>                    |
|-----------------------------------------|---------------------------------------|-------------------------------------------|
| <i><b>Experience</b></i>                | <i><b>Screen</b></i>                  | <i><b>Movement</b></i>                    |
| Experience with real-world task         | Resolution/Blur                       | Rate of linear or rotational acceleration |
| Experience with simulator (habituation) | Horizontal and vertical field of view | Self-movement speed and rotation          |
| Video game play (A)                     | Weight of the display (A)             | Vection                                   |
| Hats (A)                                | Display type                          | Altitude above terrain                    |
| Duration                                |                                       | Degree of control                         |
|                                         |                                       |                                           |
| <i><b>Physical Attributes</b></i>       | <i><b>Tracking</b></i>                | <i><b>Appearance</b></i>                  |
| Eye dominance                           | Method of movement                    | Screen luminance                          |
| Stereoscopic visual ability (A)         | Calibration                           | Color                                     |
| Postural stability                      | Position tracking error               | Contrast                                  |
| History of headaches/migraines (A)      | Tracking method                       | Scene content or scene complexity         |
| History of motion sickness              | Head movements                        | Global visual flow                        |
| BMI                                     |                                       | Orientation cues                          |
|                                         |                                       |                                           |
| <i><b>Demographics</b></i>              | <i><b>Rendering</b></i>               | <i><b>Stabilizing Information</b></i>     |
| Age                                     | Stereoscopic rendering                | Focus Areas                               |
| Gender                                  | Inter-pupillary distance              | Ratio of virtual to real world (A)        |
| Ethnicity                               | Screen distance to the eye            | Independent visual backgrounds (A)        |
| Vision correction(A)                    | Update rate                           | Sitting versus standing                   |
|                                         |                                       |                                           |
| <i><b>Mental Attributes</b></i>         | <i><b>Non Visual Feedback</b></i>     |                                           |
| Concentration level                     | Type of haptic feedback               |                                           |
| Mental rotation ability                 | Ambient temperature                   |                                           |
| Perceptual style                        | Olfactory feedback                    |                                           |
|                                         | Audio feedback                        |                                           |

**Table V: Removed Factors**

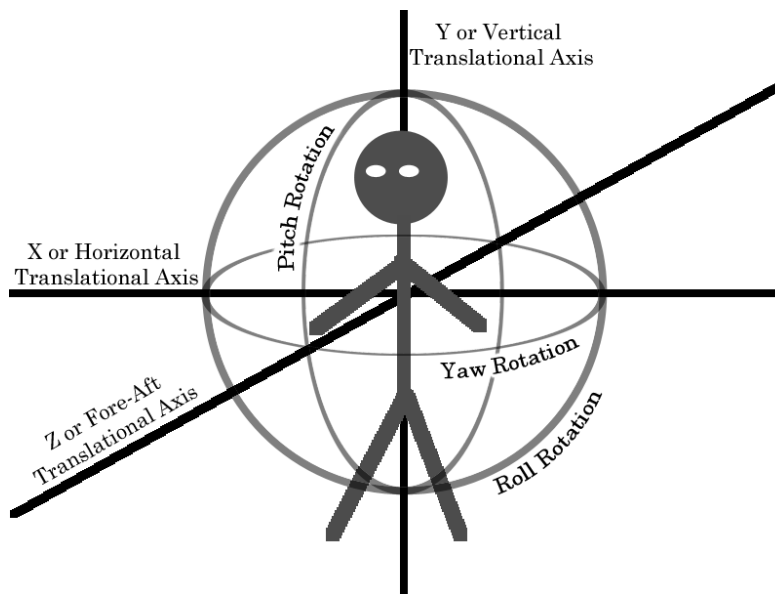
| <i>Dropped</i>                       |                    |                     |
|--------------------------------------|--------------------|---------------------|
| Illness and personal characteristics | Time lag           | Type of application |
| Flicker fusion frequency threshold   | Refresh rate       | Unusual maneuvers   |
| Phosphor lag                         | Ambient brightness | Flicker             |
| Perceptual style                     |                    |                     |

The factors are labeled as *untested*, *unlikely*, *possible*, *probable*, *confirmed*, or *conflicted*.

Confirmed factors that had sufficient support to define a model were included when developing the predictive model using all three categories. A few factors potentially required the use of sub-components in order to separate them from their primary factors for further examination.

These factors have the additional label of *partial*.

Several factors deal with direction of movement and angle of rotation. These directional and rotational axes are illustrated in Figure 3.



**Figure 3: Rotational and Translational Axes.**



### **3.1 Individual Factors**

Individual factors range from standard demographics, to mental and physical characteristics, to prior exposure to similar systems. Many of the individual susceptibility factors in cybersickness draw heavily from motion sickness studies, with the assumption being that the effects are identical for both types of sickness. Unfortunately, studies of factors such as age have decreased the reliability of these assumptions [55]. We only list the cybersickness specific studies for each factor if applicable studies exist. If no cybersickness specific studies exist, the results from motion sickness studies are used and are indicated as such.

#### **3.1.1 Demographics**

Demographics are the easiest individual factor to determine, with gender being the most commonly studied demographic feature. “Vision correction” was added as a new factor in our experiments. Vision correction implies an additional level of refraction and can, in some cases, shift display optics out of alignment with the eyes.

##### ***3.1.1.1 Age — Possible***

Until recently, virtual environment researchers assumed that susceptibility to cybersickness diminishes with age, as is the case with traditional motion sickness [57]. Motion sickness is more prevalent in younger individuals, with the effects slowly decreasing until age 50, at which time the effect plateaus. *Arns and Cern* demonstrated that this pattern curve does not apply to cybersickness [55]. They had a system that was open to visitors to their virtual reality facility and reported that the visitors who were under the age of 15 experienced less cybersickness than the adult visitors. *Park et al.* also reported a smaller percentage of early withdrawals with younger participants (13.7%) than older participants (37.3%) [56]. In contrast, *Ujike, Yokoi, and Saida*, reported a higher incidence of cybersickness in participants under the age of 30

compared with participants over the age of 30, but no statistical analysis was performed and their actual distribution of the ages was uncertain [58].

Because age is easily determined, it can be included in a general model of cybersickness. Currently, its pattern of effect is indeterminate. Recruiting older participants can be difficult. Most studies use college age participants, and most systems are not open to children or the general public.

### ***3.1.1.2 Gender — Conflicted***

There have been numerous studies regarding the effect of gender on cybersickness. Many studies report that females report more severe cybersickness symptoms, although there is some evidence that males under-report the severity of their symptoms [23,59,60]. However, some studies have found no statistical differences with respect to gender and the severity of symptoms in some cases [1,37,61].

*Harm, Taylor, and Bloomberg* [62] and *Clemes and Howarth* [63] offer two possible explanations for these disparate results. *Harm, Taylor, and Bloomberg* reported that while females reported their symptoms sooner than males, they also recovered faster than males. This means that the experimental procedures of duration and breaks can affect the cybersickness scores relative to gender demographics. *Clemes and Howarth* considered hormone levels as a possible source of explanation for the disparate results. They reported that a female participant's hormonal levels over the menstrual cycle correlated with cybersickness and that her susceptibility was higher on day 12 of a 28 day cycle. While this phenomenon may affect a female participant's cybersickness on day 12, it also means that it might not affect her cybersickness the majority of the time. Another possible explanation is that females generally

have a wider field of view [64]. Since a wider field of view influences what is seen, it may affect cybersickness.

Currently, the variation in gender studies is too high to warrant the inclusion of gender in a cybersickness model. Moreover, this variation may be due to other factors such as self-reporting reliability, general motion sickness susceptibility, visual field of view, and hormonal levels. *Graeber and Stanney's* study supports this hypothesis [65]. After balancing gender with susceptibility, there was no significant difference in their resulting SSQ-T values.

#### ***3.1.1.3 Ethnicity — Untested***

No ethnicity-specific studies were found for cybersickness. Studies in motion sickness have reported that participants of certain ethnic backgrounds report higher levels of motion sickness. *Klosterhalfen and Kellermann* reported that while Chinese participants reported a higher susceptibility than Caucasian participants, the actual degree of symptoms reported by the Chinese participants was significantly lower than that of the Caucasian participants [66]. However, many studies have reported that Chinese participants have a greater susceptibility to motion sickness compared with other ethnic groups [67,68].

#### ***3.1.1.4 Vision Correction — Untested***

Because virtual environments deal primarily with sight, any individual characteristic affecting the eyes is of interest. Stereoscopic ability has been previously examined as a cybersickness factor, but visual accuracy has not been studied. Contacts and eyeglasses require another layer of refraction before visual stimuli can reach the eye. Glasses may shift the optics of a system out of alignment. If a system does not permit glasses, as is the case with some models of Oculus

Rift, then the scene may be blurred. No cybersickness studies were found regarding vision correction, but it was included in the susceptibility survey in our experiments.

### **3.1.2 Experience**

The effect of order, or habituation, is well documented as decreasing cybersickness with repeated use. Duration of immersion is also well documented as increasing cybersickness. However, other sources of habituation such as real-world tasks, video game play, and other virtual reality configurations remain largely unstudied.

#### ***3.1.2.1 Experience with Real-World Task — Conflicted***

Because the repeated use of a virtual environment decreases reports of cybersickness, repeated use of the real world counterpart may also affect cybersickness. Participants who are familiar with the real object may be less tolerant of discrepancies, or they may have already developed a resistance to the stimuli. This is a feature of concern in training simulators. *Kolaninski* reported past research on simulation sickness in flight simulators indicated no clear correlation between a participant's experience with a real world task and cybersickness [9].

#### ***3.1.2.2 Experience with Simulator or Habituation — Confirmed, Partial***

Cybersickness studies consistently report a decrease in symptoms through habituation [69,70,71,72,73]. However, how long this effect lasts is less certain. *Stanney and Kennedy* suggest having sessions every two to five days to encourage habituation [69]. *Howarth and Hodder* had participants return ten times, and spaced the sessions two to seven days apart [72]. All the conditions resulted in a significant decrease in symptoms, with 50% of the participants reporting no symptoms at the end of the experiment. *Regan's* study implies that this effect may be limited for participants that return four times [74]. In *Regan's* study, the spacing between

the first, second, and third sessions was four months, while the spacing between the third and fourth sessions was one week. The participants reported a decrease in their symptoms between the first and second session, which was likely due to the reduced novelty of the system and any coping strategies that may have been learned. We noticed a similar effect in our own experiments where some participants in their second sessions would display markedly different interactions with the system compared with their first sessions. There was almost no change in participants' symptoms between *Regan's* second and third sessions, but there was an additional decrease in their symptoms between the third and fourth sessions. This implies that loss of habituation can occur over time periods between one week and four months.

One limitation of this approach is that it is unknown whether other virtual environment systems also help to develop habituation. This includes stereoscopic movies, which contain similar visual stimuli. Here, the habituation effect is difficult to determine, as the change in display may also affect the level of cybersickness. For habituation to be examined with stereoscopic movies, the effect of the display would need to be normalized.

The habituation value reports from the above studies are shown in Table VI. We include our results if we had a sufficient number of participants within a given time period. For example, less than 5 of our participants had 20+ days between sessions, which was not a large enough sample to reliably calculate statistical significance. Our experiments include display weight (*Our HMD*), size of the screen (*Our Screen*), and stereoscopic rendering (*Our Render*) and are described in more detail in Section 4. Studies that only reported the number of people who did not become ill, rather than an estimate of symptoms, are not included in Table VI.

The values in Table VI seem erratic upon initial inspection. For example, the decrease in the absolute values of the SSQ differs substantially between the weight and screen experiments. But upon closer inspection, the percentages of decrease are more consistent, and *Howarth and Hodder's* study implies that the percentage of decrease remained fairly consistent even with multiple repeat sessions. The literature habituation values are combined with our own in Figure 4. While the constancy has improved over the original SSQ-T values, the data points are not well grouped besides the fact that they are generally less than 0. Part of this lack of consistency is due to a difference in applications and initial symptoms. Our study had the highest reported initial SSQ-T, and therefore had the greatest potential to decrease symptoms through habituation. The average decrease in symptoms was 11.8%. Therefore, using an 11.8% or 0.882 decrease per session, the formula to predict habituation with the same virtual environment configuration is:

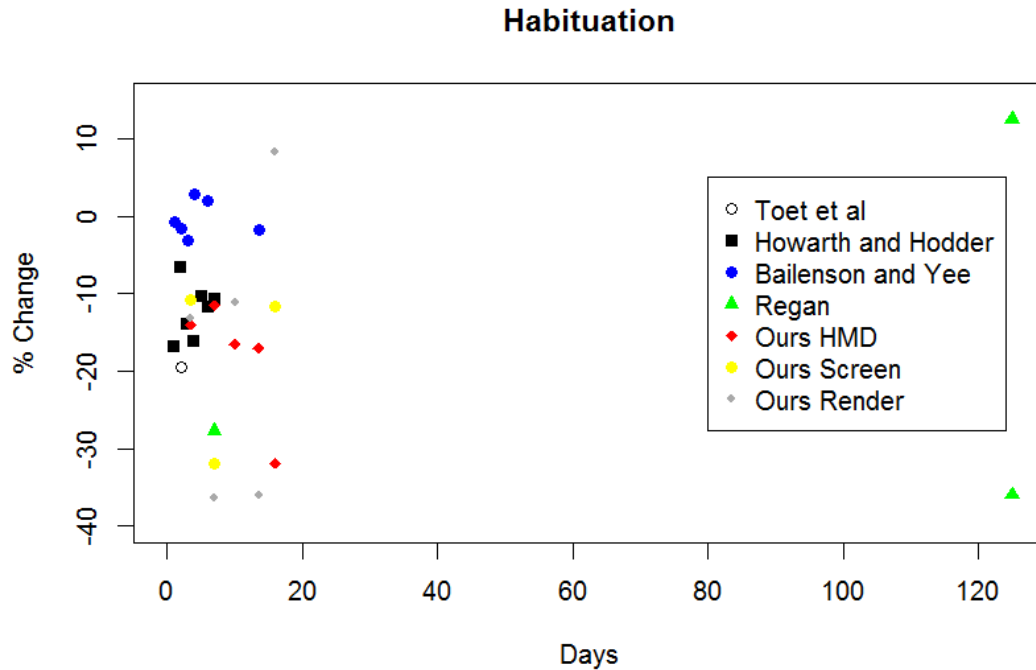
$$Habit(A) = 0.882^{a_{order}-1} \quad 1$$

Where  $A$  is the virtual environment configuration factor vector and  $a_{order}$  is the number of the current session. This formula results in an exponential decay of symptoms over time. The duration of habituation remains unknown, partially because habituation resulting from a participant's first use of a system seems to last longer than habituation resulting from subsequent sessions, possibly due to the participant's learning of coping mechanisms. Therefore, a minimum of three sessions are required to study long term habituation: the first to learn coping mechanisms, the second to create the baselines for a participant, and the third to analyze the decrease in symptoms.

**Table VI: Habituation Values**

|                | <b>Study</b>                                  |                                        |                                        |                                        |                                                                                          |
|----------------|-----------------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|------------------------------------------------------------------------------------------|
|                | <i>Toet et al.<br/>[71]</i>                   | <i>Howarth and<br/>Hodder [72]</i>     | <i>Bailenson<br/>and Yee [73]</i>      | <i>Regan<br/>[74]</i>                  | <b>Ours1</b>                                                                             |
| <b>Measure</b> | <i>MISC Dif.<br/>0-10 (MISC<br/>% Change)</i> | <i>SSQ Dif.<br/>(SSQ %<br/>Change)</i> | <i>SSQ Dif.<br/>(SSQ %<br/>Change)</i> | <i>SSQ Dif.<br/>(SSQ %<br/>Change)</i> | <i>HMD, Screen, Rendering<br/>SSQ Dif.<br/>(HMD, Screen, Rendering<br/>SSQ % Change)</i> |
| <b>Time</b>    |                                               |                                        |                                        |                                        |                                                                                          |
| <b>1</b>       |                                               | -1.44<br>(-16.87)                      | -0.01<br>(-0.674)                      |                                        |                                                                                          |
| <b>2</b>       | -0.575<br>(-19.54)                            | -1.44<br>(-6.65)                       | -0.02<br>(-1.53)                       |                                        |                                                                                          |
| <b>3</b>       |                                               | -1.78<br>(-14.02)                      | -0.05<br>(-3.07)                       |                                        |                                                                                          |
| <b>4</b>       |                                               | -1.5<br>(-16.25)                       | 0.025<br>(2.93)                        |                                        |                                                                                          |
| <b>5</b>       |                                               | -1.16<br>(-10.45)                      |                                        |                                        |                                                                                          |
| <b>6</b>       |                                               | -1.33<br>(-11.8)                       | 0.0<br>(2.017)                         |                                        |                                                                                          |
| <b>7</b>       |                                               | -1.33<br>(-10.64)                      |                                        | -5<br>(-27.7)                          | -7.06, -0.4, -12.15<br>(-11.54, -32, -36.3)                                              |
| <b>13, 14</b>  |                                               |                                        | -0.02<br>(-1.71)                       |                                        | -10.9, 7.48, -2.49<br>(-17.09, 28.57, -36)                                               |
| <b>1-7</b>     |                                               |                                        |                                        |                                        | -3.74, -1.36, -5.236<br>(-14, -10.74, -13.21)                                            |
| <b>8-12</b>    |                                               |                                        |                                        |                                        | -7.95, NA, -18.7<br>(-16.56, NA, -11.19)                                                 |
| <b>13-19</b>   |                                               |                                        |                                        |                                        | -8.58, -0.63, -3.74<br>(-31.9, -11.72, 8.33)                                             |
| <b>125</b>     |                                               |                                        |                                        | -9, 2<br>(-36, 12.5)                   |                                                                                          |

<sup>1</sup> We had a few participants that started with a score of 0 and later increased, resulting in division by 0 errors. To compensate for this, small SSQ-T changes (< 4) were ignored, and large changes were assigned a 100% increase.



**Figure 4: Habituation Data**

### ***3.1.2.3 Video Game Play — Untested***

Since the repeated use of a system decreases reports of cybersickness, it is possible that visual stimuli that are similar in nature to the virtual environment might also decrease cybersickness. Many console video games and some computer games provide visual stimuli that are similar to virtual reality stimuli. While motion sickness has been reported with video game play [30], no studies were found that examined if video game play could help create habituation to virtual environments. This factor was included in a background survey in our experiments.

### ***3.1.2.4 Hats — Untested***

The inclusion of hats in our initial susceptibility survey was included for three reasons: Tight bands may cause headaches [75,76], some participants dislike any additional weight on their heads, and the center of mass on the head is altered. Because head mounted displays are worn



on the head, participants that wear hats may be more tolerant of head mounted displays. No prior cybersickness specific studies were found for this factor.

### **3.1.2.5 Duration — Confirmed**

It is well known that longer durations of virtual environment use correlate with a higher frequency and severity of cybersickness [23,29,74,77,78,79,80]. Stanney *et al.* reported on the proportion of participants that withdrew early at various duration times [81]. Of the participants that had a 15 to 60 minute session, 20% of them did not finish their session. Of those that withdrew, 50% withdrew after 11 to 20 minutes of exposure, 20% withdrew after 21 to 30 minutes of exposure, and 20% withdrew after 31 to 40 minutes of exposure.

The task of comparing the SSQ values from different configurations with different exposure times is error prone, and there is currently no method available to normalize the effect of such configuration changes. Therefore, cybersickness models must be based on a percentage change in symptoms. The values and percent changes in Table VII summarize the above systems. Regan mentions that participants withdrew due to dizziness, which occurred in our experiments as well. It can be argued that nausea alone is not a sufficient monitoring measure and therefore the values were transformed into an SSQ-T estimate for comparison.

The results have been combined and fitted to the linear models shown in Figure 5. The average SSQ-T effect, where  $A$  is the virtual environment configuration factor vector and  $a_{minutes}$  is the number of minutes, is:

$$Time(A) = 1.42 a_{minutes} + 6.83 \quad 2$$

**Table VII: The Results of Several Duration Studies**

| <i>Study</i>                          | <i>Measure</i>           | <i>Time in Minutes</i>  |                            |                         |                          | <i>SSQ Estimate</i> |
|---------------------------------------|--------------------------|-------------------------|----------------------------|-------------------------|--------------------------|---------------------|
| <b>Stanney et al. [23]</b>            |                          | 15                      | 30                         | 45                      | 60                       |                     |
|                                       | SSQ-T                    | 20                      | 26                         | 29                      | 32                       |                     |
| <b>So, Lo and Ho [15]<sup>1</sup></b> |                          | 5                       | 10                         | 20                      | 30                       |                     |
|                                       | Nausea ratings (0-6)     | 0.1, 0.3, 0.1, 0.4, 0.7 | 0.25, 0.75, 0.3, 0.8, 1.75 | 0.9, 1.4, 1.2, 1.6, 2.7 | 1.75, 2.2, 2.1, 2.4, 3.6 | 30, 34, 26, 48, 47  |
| <b>So and Lo [78]</b>                 |                          | 5                       | 10                         | 15                      | 20                       |                     |
|                                       | Nausea ratings (0-6)     | .78, .75, .8, 0         | 1.25, 1.1, 1.4, 0          | 1.5, 1.25, 1.5, 0.25    | 1.55, 1.6, 1.5, 0.4      | 30, 34, 38, 15      |
| <b>Stanne et al. [79]</b>             |                          | 15                      | 30                         | 45                      | 60                       |                     |
|                                       | SSQ-T                    | 16                      | 22                         | 33                      | 35                       |                     |
| <b>Ours</b>                           |                          | 3                       | 6                          | 9                       | 12                       |                     |
|                                       | Immersion ratings (0-10) | 0.25, 0.47, 0.34        | 0.64, 0.74, 0.86           | 1.27, 1.02, 1.58        | 1.98, 1.29, 2.18         | 27.26, 21.22, 32.97 |
|                                       |                          | 15                      | 18                         | 21                      | 24                       |                     |
|                                       | Immersion ratings (0-10) | 2.27, 1.51, 2.84        | 2.57, 1.77, 3.14           | 3, 2.02, 3.5            | 3.34, 2.31, 4.02         |                     |
| <b>Moss and Muth [82]</b>             |                          | 0                       | 1.5                        | 5                       | 10                       |                     |
|                                       | SSQ-T                    | 1.79                    | 7.38                       | 9.79                    | 13.88                    |                     |
|                                       |                          | 15                      | 20                         | 25                      |                          |                     |
|                                       | SSQ-T                    | 18.85                   | 24.49                      | 32.33                   |                          |                     |

Table VII (cont'd)

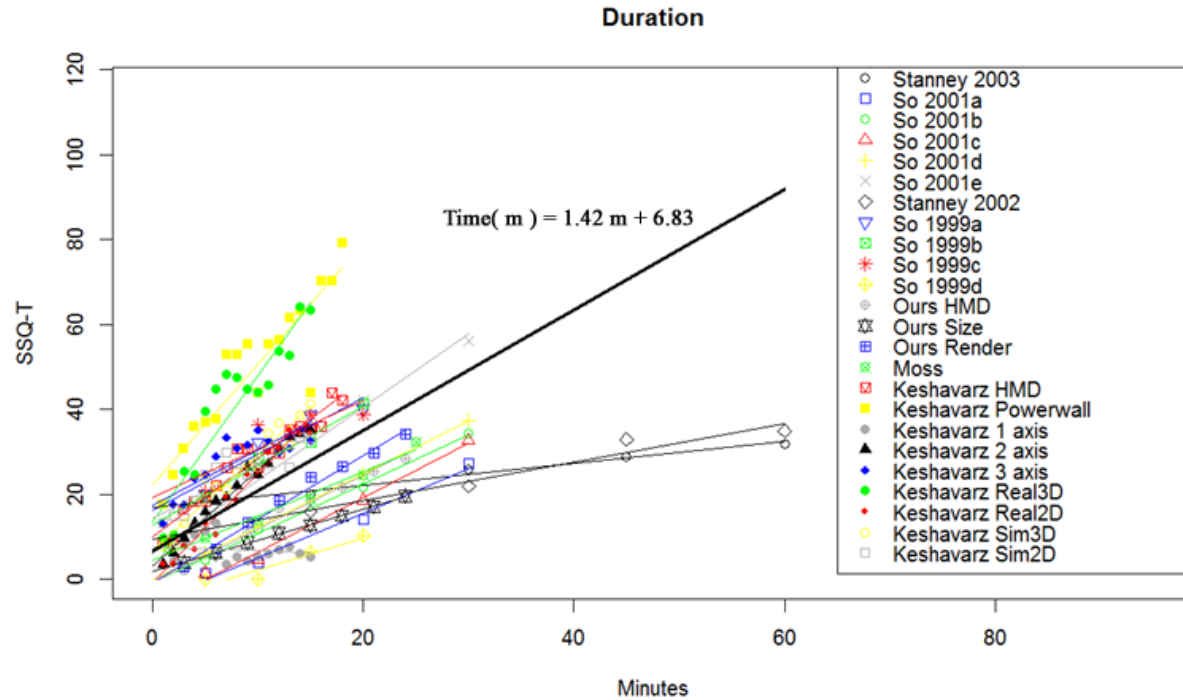
| <b>Keshavarz studies<br/>HMD,<br/>PowerWall<br/>[82] (pitch,<br/>pitch/roll,<br/>pitch/roll/yaw) [83] [real<br/>3d, real 2d,<br/>sim 3d, sim<br/>2d][84]</b> |                   | 1                                                 | 2                                               | 3                                                 | 4                                                 |                                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|---------------------------------------------------|-------------------------------------------------|---------------------------------------------------|---------------------------------------------------|----------------------------------|
|                                                                                                                                                              | <i>FMS (0-20)</i> | 0.5, 0.3<br>(0.4, 1.5)<br>[1.1, 0.4,<br>0.9, 1.5] | 1, 1.9<br>(0.7, 2)<br>[1.2, 0.4,<br>0.9, 1.7]   | 1, 2.8<br>(1.1, 2)<br>[2.9, 0.9,<br>1.5, 1.7]     | 1.9, 3.5<br>(1.5, 2.7)<br>[2.8, 0.8,<br>2.1, 2.1] |                                  |
|                                                                                                                                                              |                   | 5                                                 | 6                                               | 7                                                 | 8                                                 | (20, 21,<br>30) <sup>2</sup>     |
|                                                                                                                                                              | <i>FMS (0-20)</i> | 2.1, 4.1<br>(1.8, 2.8)<br>[4.5, 1.5,<br>2.7, 2.8] | 2.1, 4.2<br>(2.1, 3.3)<br>[5.1, 1.2,<br>2.5, 3] | 2.5, 4.3<br>(2.2, 3.8)<br>[5.5, 2.2,<br>2.4, 3.4] | 3, 6<br>(2.5, 3.5)<br>[5.4, 2.1,<br>2.9, 3.1]     |                                  |
|                                                                                                                                                              |                   | 9                                                 | 10                                              | 11                                                | 12                                                |                                  |
|                                                                                                                                                              | <i>FMS (0-20)</i> | 3.5, 6<br>(3, 3.6)<br>[5.1, 2.8,<br>3.1, 2.8]     | 3.5, 6.3<br>(2.8, 4)<br>[5, 2.9, 3, 3]          | 3, 5.5<br>(3.1, 3.7)<br>[5.2, 3.4,<br>3.9, 3.1]   | 3.5, 6.3<br>(3.5, 3.4)<br>[6.1, 3.5,<br>4.2, 3.5] | [38, 40,<br>44, 37] <sup>2</sup> |
|                                                                                                                                                              |                   | 13                                                | 14                                              | 15                                                | 16                                                |                                  |
|                                                                                                                                                              | <i>FMS (0-20)</i> | 3.4, 6.4<br>(3.8, 3.5)<br>[6, 4, 3.6,<br>3.0]     | 4, 7<br>(3.9, 4)<br>[7.3, 3.9,<br>4.4, 3.8]     | 4.1, 7.2<br>(4, 3.7)<br>[7.2, 3.9,<br>4.7, 3.8]   | 4, 6.5                                            |                                  |
|                                                                                                                                                              |                   | 16                                                | 17                                              | 18                                                |                                                   |                                  |
|                                                                                                                                                              | <i>FMS (0-20)</i> | 4.1, 8                                            | 5, 8.8                                          | 4.8, 9                                            |                                                   |                                  |

<sup>1</sup> So, Lo, and Ho suggested that their results after 10 meters per second may be inaccurate due to early withdrawals.

<sup>2</sup> The multiplier was averaged from these two studies for the graph.

### 3.1.3 Mental Attributes

Mental attributes are one of the most difficult individual features to include in susceptibility tests. They generally require additional tests that are not readily available for use at home. However, they may be beneficial for identifying the limits on virtual environment design and explaining other poorly understood attributes such as gender.



**Figure 5: Fitted Duration Values**

### **3.1.3.1 Concentration Level — Probable**

Concentration level refers to both the participant's sense of "being" in the virtual world rather than firmly identifying it as a simulation, and the participant's concentration on the task in a virtual environment. Demand characteristics state that if a person expects a particular response, that response is more likely to occur. Concentration may diminish demand characteristics by distracting a participant from undesirable effects such as cybersickness, and *Young, Adelstein, and Ellis* [36] and *Nichols et al.* [6] support this hypothesis. *Young, Adelstein, and Ellis* studied participants' post-immersion scores with and without the administration of a pre-immersion test. The SSQ scores of the post-test were higher when a pretest was given, with nausea being the most affected symptom. The change in SSQ-N was only a third as high without the administration of a pretest.

*Nichols et al.*'s second experiment tested the correlation between participants sensing the presence of an "interface" and cybersickness where the "interface" was defined as: "...whether the interaction devices or display quality interfered with the virtual experience, and how well participants felt they could concentrate on the tasks in the virtual environment." They found a negative correlation between the "interface" and cybersickness. *Yang and Sheedy* reported that although a stereoscopic movie produces more symptoms, participants also reported a greater focus on their tasks. [85]

The effect of a participant's concentration on a task is less certain. On one hand, concentration may decrease participants' monitoring of their physical state, which would decrease cybersickness. However, if the task causes physical strain it could increase cybersickness. For example, if the virtual content is difficult to read, participants may strain their eyes to read it. This eye strain might then increase cybersickness.

### ***3.1.3.2 Mental Rotation Ability — Conflicted***

Because virtual environments are three dimensional, a more intuitive understanding of three dimensional spaces may affect cybersickness in some participants. *Kolasinski* reported that improved mental rotation ability increased cybersickness in females, but this effect was reversed for males [1]. However, mental rotation ability was a secondary variable under examination and statistics were not reported. In addition, mental rotation ability differs between the standard two-dimensional pen and paper test and three-dimensional virtual environments tests. *Parson et al.* reported that while males performed better on two-dimensional mental rotation tests, there was no difference between males and females when

they were tested in a virtual environment [86]. The impact of this factor remains uncertain and requires further study.

### **3.1.3.3 Perceptual Style — Possible**

Perceptual style includes how a participant views a system. Traditionally, it is how a person determines what is vertical or "up" in a given situation. Participants who are field-dependent determine what is "up" from external visual sources. Participants who are field-independent determine what is "up" using internal vestibular sources. This is frequently tested with the "rod and frame test" wherein subjects attempt to adjust a rod to true vertical inside a frame that has been pivoted away from true vertical. *Barret and Thornton* reported that 18 of their 39 of field-independent subjects withdrew early while 5 of their 7 field-dependent subjects withdrew early [87]. Initially, this implies that being field dependent increases the likelihood of cybersickness symptoms. However, all the extremely field-independent participants withdrew early. The authors suggest that this discrepancy may be due to the consistency of the participants' responses to the rod and frame test rather than field-dependence. Due to the requirement of special equipment to test perceptual style, it is difficult to include in a cybersickness prediction model.

### **3.1.4 Physical Attributes**

Physical attributes are somewhat more easily identified than perceptual styles. Eye dominance is a ten second test that can be easily conducted without any special equipment. However, factors such as stereoscopic visual ability require longer tests and measures of postural instability require special equipment. Of the physical attributes, a past history of motion

sickness and headaches/migraines hold the greatest promise for inclusion in a cybersickness prediction model.

#### ***3.1.4.1 Eye Dominance — Unlikely***

Most people have one eye that is favored over the other eye. Since menu options or interface controllers are often placed on one side of the screen, one eye may witness a larger proportion of important details than the other eye. This is particularly problematic for single eye displays, which may decrease the accuracy for participants with a dominant opposite eye [88]. Most displays engage both eyes, and Ling *et al.* found no correlation between cybersickness and eye dominance [37]. However, due to their use of independent T-tests, their statistical accuracy is questionable. T-tests are not ideal for cybersickness studies because the results of cybersickness studies are highly dependent on the individual.

#### ***3.1.4.2 Stereoscopic Visual Ability — Unlikely***

Stereoscopic systems mimic the natural disparity in images that each eye sees. However, certain individuals are more sensitive to stereoscopic rendering and other individuals may lack this ability completely. The ability to process stereoscopic rendering is referred to as *stereoscopic acuity*. Hale and Stanney tested each participant's stereoscopic acuity and then gave them tasks to perform in a virtual environment [89]. While with the participants with poor acuity tended to travel farther in virtual environments, the authors reported no statistical difference in the symptoms of the low and high stereoscopic acuity groups. While the Hale and Stanney study reported no difference, one study is not conclusive regarding the effect of stereoscopic acuity. However, testing for stereoscopic disparity requires special equipment and takes time, which makes it less desirable for use in a cybersickness prediction model.

#### **3.1.4.3 Postural Instability — Confirmed**

Postural instability has been correlated with cybersickness in numerous studies

[31,40,61,90,91,92,23]. As mentioned earlier, postural instability is gaining favor as a cybersickness symptom measurement. Current postural instability research typically measures changes in the X and Z axes as shown in Figure 3, with the Z axis being the axis that is most highly affected by cybersickness. The summary statistics typically used in postural instability research include the average variability and velocity along a given axis. Typical locations for the position sensors used in postural instability studies include the base of the neck and torso, although *Bos et al.* employed a Nintendo Wii Balance Board [92].

Unfortunately, postural instability's use as a predictive measurement has not been developed, with only *Smart, Otten, and Stoffregen* discussing the potential use of discriminate functions [20]. Different authors report diverse values for their results, and the sampling rate, data filtering, and position of the sensors vary between the postural instability studies reported in the literature.

#### **3.1.4.4 History of Headaches/Migraines — Possible**

Recently, researchers studying illness during the viewing of stereoscopic movies have found a correlation between a past history of headaches/migraines and illness [93]. Headaches are included as a symptom in the SSQ, and there are many similarities between stereoscopic movies and virtual environments. Therefore, a history of headaches may increase the likelihood of cybersickness. This factor was included in our updated usability survey.



#### **3.1.4.5 History of Motion Sickness — Probable**

Cybersickness researchers often assume that the same factors that affect motion sickness also affect cybersickness, with a potentially different symptomology. Therefore, a susceptibility to motion sickness may imply a susceptibility to cybersickness. The inclusion of a past history of motion sickness is not particularly common amongst cybersickness researchers, and the only researchers that have employed it are *Stanney et al.* [23], *Toet et al.* [71], *Bos et al.* [94], and *Van Emmerik, de Vries, and Bos* [49]. *Stanney et al.* found a correlation between cybersickness and a past history of motion and carnival ride sickness. *Bos et al.* and *Van Emmerik, de Vries, and Bos* included a past history of motion sickness as a factor, but did not test for its correlation with cybersickness. *Graeber and Stanney* tested both past history of motion sickness and gender, and found a correlation that was due to a past history of motion sickness only [65]. However, *Stanney et al.* did not find a correlation between their motion sickness history questionnaire (MHQ) and SSQ-T [17]. This factor was included in our experiments, and we found a correlation with cybersickness that will be discussed in Section 5.5.2.

#### **3.1.4.6 Weight and Body Mass Index — Possible**

*Taha et al.* [95] and *Stanney et al.* [23] tested the effect of a participant's weight on cybersickness. *Taha et al.* examined raw weight and found no effect, but *Stanney et al.* did find a correlation between a participant's body mass index (BMI) and the SSQ-O [23]. Given that BMI may not be readily available and has a minor effect on overall cybersickness, it may be difficult to add BMI to a predictive cybersickness metric.

### **3.2 Hardware Factors**

Virtual environments have a wide variety of configurations due to application and hardware limitations. There are multiple rendering, tracking, display, and environment options. Of these,

the display has become the most recent hardware factor of interest to cybersickness researchers. The field of view of a screen has shown some of the strongest effects on cybersickness in the hardware category of factors.

### **3.2.1 Rendering**

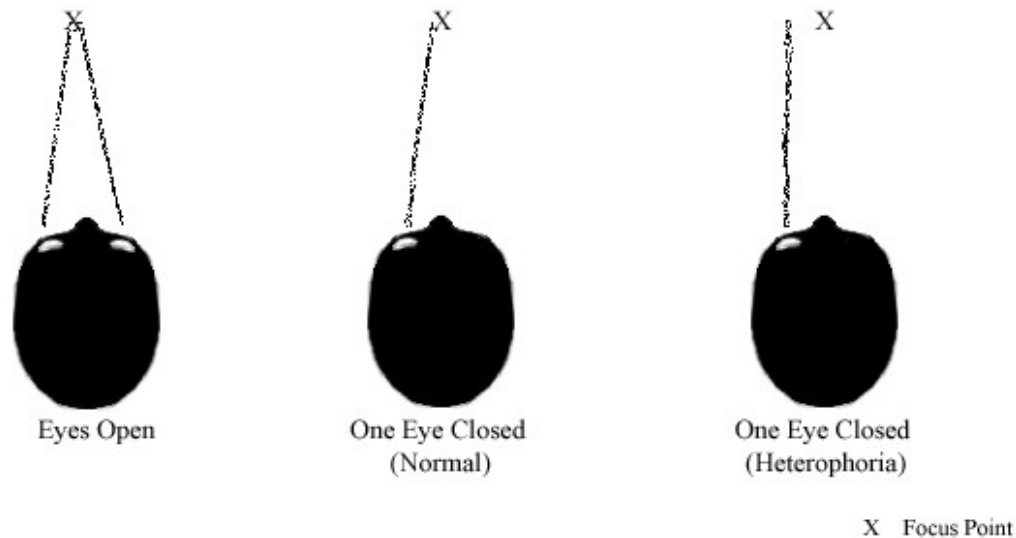
Rendering factors relate to how a scene is created and displayed. Stereoscopic rendering, field of view (FOV) and interpupillary distance have generated the most interest for cybersickness studies. Many cybersickness researchers who study stereoscopic rendering use eye function rather than the SSQ as their measurement. Thus, their research is inconclusive regarding how these features affect cybersickness, because eye function only relates to the oculomotor category of the SSQ.

#### ***3.2.1.1 Stereoscopic Rendering — Conflicted***

Stereoscopic movie participants have an anecdotally higher reporting of illness than monoscopic movie participants. Therefore, a stereoscopic virtual environment may also induce more incidents of cybersickness than a monoscopic virtual environment. Stereoscopic, bi-ocular, and monoscopic displays all cause strain on the eyes that may affect their normal function. However, many studies on stereoscopic rendering use eye function rather than the SSQ as their measurement. How stereoscopic rendering actually affects overall cybersickness is unknown, but the measure of choice in the literature is heterophoria.

Heterophoria is defined as a deviation of eye position that is normally suppressed with stereo fusion. This means that one eye moves from its resting position if the other eye is covered or if stereo fusion has been inhibited by other means (see Figure 6 ). Heterophoria can be measured by several different methods and is often clinically measured with a prism and a cover-uncover

test. For more details on the techniques used to measure heterophoria, see *Rainey et al.* (Rainey et al. 1998). Most individuals have a minor amount of heterophoria, but this may be affected by near or far sightedness. All the following heterophoria results are for horizontally shifted heterophoria.



**Figure 6: Heterophoria**

*Mon-Williams, Wann, and Rushton* found that after 10 minutes of stereoscopic HMD use, all but one of their participants had a significant increase in heterophoria, while a bi-ocular display had little effect after 30 minutes of use [16]. *Howarth* found the opposite result, i.e., no change in heterophoria with stereoscopic bi-ocular displays [96]. Unfortunately, the stereoscopic interpupillary distance (IPD) used in *Howarth's* study was set to an average IPD while the bi-ocular displays were set to be either lower or higher than the average IPD. Therefore it is uncertain if their results were due to IPD or rendering. *Karpicka and Howarth* reported an increase in heterophoria with a stereoscopic display, but not with a monoscopic display [97]. However, heterophoria did not affect the level of discomfort of the participants.

*Mon-Williams and Wann* demonstrated the importance of the task when studying the effect of stereoscopic displays [98]. They found that shifting a focus point along the Z axis resulted in an increase in heterophoria when focusing at a distance. *Yang and Sheedy* demonstrated that a stereoscopic movie produces a greater variance in vergence and accommodation than a monoscopic movie, and that the vergence and accommodation are farther from ideal in a stereoscopic versus monoscopic setting [85].

There have been a few studies using the SSQ as a measurement, but the results are unclear. *Hakkinen, Vuori, and Paakka* reported higher cybersickness scores for participants playing a stereoscopic game using an HMD than for those watching a bi-ocular movie using an HMD or watching a movie with a normal screen [61]. Unfortunately, due to the different visual stimuli between the conditions, the SSQ measurement effect was uncertain. *Ehrlich* reported only that the SSQ-N was higher during stereoscopic versus bi-ocular rendering [39]. *Kershavarz and Hecht* compared real stereoscopic video of a rollercoaster, a stereoscopic rendering of a three-dimensional model of the same rollercoaster, and a monoscopic version of the real and modeled rollercoasters [84]. They reported no significant differences between the conditions, although the real stereoscopic rollercoaster cybersickness scores trended higher.

Experimental results support that there is no difference in cybersickness symptomology using bi-ocular vs. monoscopic rendering. *Kershavarz, Hecht, and Zschuttschke* reported that there was no difference between bi-ocular and monoscopic rendering with respect to cybersickness [82]. They specifically tested whether the differences reported between using a large monoscopic screen and a bi-ocular HMD were due to rendering or some other factor. They

created a device called a "synopter" that converts a large screen into a bi-ocular arrangement. They found no difference in cybersickness between the participants using the monoscopic and bi-ocular conditions.

*Kolasinski* examined IPD correlations with the SSQ-O, SSQ-D, and eyestrain [1], and only found a correlation with eyestrain.

### ***3.2.1.2 Inter-Pupillary Distance — Possible***

To correctly render a stereoscopic virtual environment, the spacing between the rendering frustums should be aligned with the participant's eyes. The spacing between the pupils of the eyes is called the *inter-pupillary distance* (IPD). If the software and hardware alignment differs from the IPD, the stereoscopic presentation will be flawed. In practice, near-perfect alignment rarely occurs, as both the software and hardware must align the images correctly to each individual. Many systems do not provide this option, and when they do, special equipment is often needed to accurately measure the IPD. The average IPD is 64 millimeters.

*Howarth* measured heterophoria during his investigation of various HMD configurations [96]. Three different HMDs were tested. The first was bi-ocular with a 60 millimeter interpupillary distance (IPD), the second was bi-ocular with a 70 millimeter IPD, and the third was stereoscopic with an IPD of 64 millimeters. Although all three configurations caused heterophoria, they found no correlation between the level of IPD disparity and heterophoria. However, there was a trend inward for the first and third HMDs and outward for the second HMD, which were the smaller and larger IPDs, respectively. *Kolasinski and Gilson* reported that the strain on the eye became more severe the more dissimilar the display's IPD was with the participant's physical IPD [99].

### ***3.2.1.3 Screen Distance to the Eye — Untested***

When focusing on an object, the eye's vergence and accommodation adjust to that object. In physical settings, the focus depth for accommodation is the same as the depth for vergence. In virtual environments, the distance to the screen remains fixed, which means that vergence will resolve content at a different depth than the focus depth. Theoretically, the more the distance between vergence and accommodation differs, the greater the potential for cybersickness. Differences between the physical screen and virtual object locations lead to differences in vergence and accommodation. There are no published studies regarding this phenomenon, but this is a factor under consideration in our experiments.

### ***3.2.1.4 Update Rate — Conflicted***

Lag is a delay in visual stimuli relative to tracking or other physical measures. Lag is the sum of such delays due to the acquisition time of tracking sensors, the rendering time for computer graphics, and the delay of the presentation of the next frame. Because it impacts response time, lag has been of significant interest in simulator research.

As lag increases, visual and vestibular information begin to deviate from each other. According to sensor mismatch theory, this should increase cybersickness. However, the research results have been conflicting. *Draper et al.* used a panorama with a 48, 125, or 250 millisecond delay [50]. They found no statistically significant difference between the conditions, but there was a trend of more cybersickness in the 125 millisecond condition. *Kinsella* argues that a constant length of delay is not the issue, rather, it is that the length of the delay can vary over time [100]. Although *Kinsella* reported that significance was not reached with a regular ANOVA, a faster variance (1 Hz) in the length of the delay induced more symptoms than a slower variance (0.2

Hz). *Dizio and Lackner* tested 67, 100, 200, and 300 millisecond delays [101]. They reported symptom increases with the delays. However, a comparison across the delays was not reported.

The degree to which lag affects cybersickness is uncertain, but a minimum update time of 60 Hz is a standard requirement for display systems. If all aspects of tracking, rendering, and displaying are not accomplished within that time, there is too much lag. Even the smallest lag in the above studies is unacceptable by current standards.

### **3.2.2 Tracking**

There are many different options for tracking an individual. Some researchers choose not to track participants at all and use a chin rest to guarantee identical visual stimuli. Other researchers use full 6 degree-of-freedom tracking, as shown in Figure 3, although any one of the six degrees of freedom may be used independently. Correct tracking is necessary to render the appropriate image, but all types of tracking add an unavoidable delay due to the transmission of position data. Tracking also includes the controllers used by a system, which means that movement can be due to the physical motion of a participant, a controller such as a joystick, gestures, and/or forced movement due to the application.

#### **3.2.2.1 Method of Movement — Probable**

Sensor mismatch theory proposes that a better match between the real world and virtual world will result in lower levels of cybersickness. Theoretically, a more natural movement should induce lower levels of cybersickness. There are three sources of movement: movement due to a participant's body, movement due to a controller, and movement forced by the application. Most interactive systems use all three sources of movement. For example, the direction a

participant faces may control the orientation of the viewpoint, a joystick might specify how fast a participant moves in space, and collision control may force the viewpoint away from a wall.

Research comparing movement methods supports the use of more natural movement. *Jaeger and Mourant* compared the forward motion controlled by a treadmill versus a 2D mouse [59]. The treadmill condition exhibited lower sickness scores than the mouse condition. Similarly, *Chen, Plancloulaine et al.* compared two interfaces: a joystick and head/body position [102]. They found that the head/body condition exhibited lower cybersickness scores and performed better than the joystick condition.

### ***3.2.2.2 Calibration — Untested***

Rest frame theory postulates that cybersickness should decrease with virtual environment movement predictability. What is expected may vary from individual to individual, and a virtual environment can be calibrated to a specific individual. For example, *Jaekl, Jenkin, and Harris* reported that participants typically misjudge their distance traveled in a virtual environment, reporting that they traveled 1.2-1.4x farther than they were estimated to travel in these systems [28]. A one-time calibration sequence can be performed to determine individual estimation bias. No studies directly testing the effect of calibrations on cybersickness could be found in the literature.

### ***3.2.2.3 Position Tracking Error —Possible***

In general, virtual environments try to match real world positions and orientations as closely as possible. An incorrect alignment can cause sensory mismatch, and therefore cybersickness. One study indirectly tested tracking errors. *Kinsella* tested different latency frequencies and amplitudes [100]. Although the effects were not significant, varying the latency, and therefore



the tracking error, consistently increased cybersickness symptoms. Because cybersickness is highly individualistic and frequently non-normalized, *Kinsella's* conventional ANOVA analysis may have hidden the effect of position error. In addition, position error may interact with certain characteristics of the application, as some applications are more tolerant than others of positional errors as long as the degree of error remains relatively stable. This is particularly true for orientation as it is used in applications that over-rotate the scene to prevent people from walking into physical walls.

#### ***3.2.2.4 Tracking Method — Conflicted***

Some cybersickness studies use chin rests rather than head tracking, so it is reasonable to consider the advantages and disadvantages of head tracking. *Howarth and Finch* examined the nauseagenic effects of HMDs with and without head tracking [103]. They found that head tracking caused a greater sickness rating within eight minutes of exposure, and that the ratings gap between the two conditions continued to increase with time. McGee also reported increased illness with head tracking [104]. These results are in conflict with both movement studies and sensor mismatch theory, and further study is warranted. In addition, the axes that need to be tracked are unknown. For example, tracking just the orientation axes may be sufficient. In addition, the tracked y-position, or the participant's height, is rarely altered in many virtual environments.

#### ***3.2.2.5 Head Movements — Untested***

There are anecdotal reports in the literature that some participants use a coping mechanism of slowing their head movement when they feel ill. This implies that if a system requires a large amount of head motion, cybersickness may increase. Tracked and non-tracked studies have

been performed, but no study was found comparing systems requiring large versus small amounts of head movement.

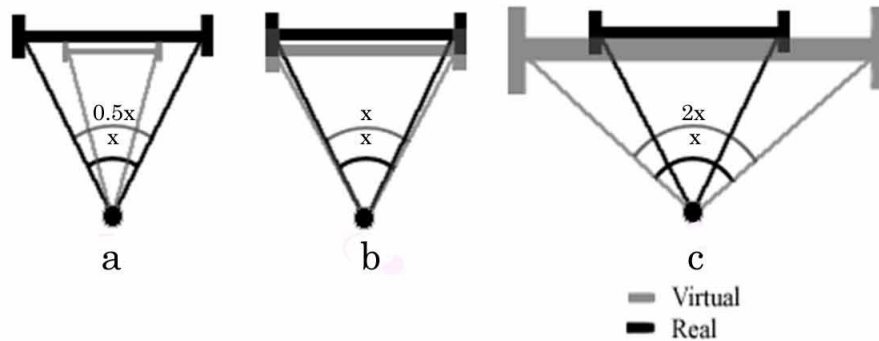
### **3.2.3 Screen**

Screen quality and size have been topics of concern in virtual environments for decades. Early head mounted displays were large, heavy, and unwieldy, and often required the use of counterweights. The newer head mounted displays are lighter and more comfortable, but often have lower-quality optics. Large screens, whether they are projected, utilized across multiple small screens, or simply consist of a very large television screen, are an alternative to head mounted displays. However, they restrict the direction in which a participant may face and may require a participant to stand to achieve the benefits of head tracking.

#### ***3.2.3.1 Resolution/Blur — Possible***

Low resolution or highly blurred scenes may decrease participants' use of virtual reality stimuli, causing them to rely on real world stimuli instead. This would likely cause a decrease in cybersickness symptoms as there is less of a potential mismatch between the two types of stimuli. Additionally, most virtual reality systems do not include motion blur, which may result in a flickering or lag type effect that might increase cybersickness. Conversely, some researchers state that low refresh rates results in blur due to eye movements and will increase cybersickness. These factors have not been explored in detail, although *Mon-Williams, Wann, and Rushton* cited resolution improvements that potentially increased cybersickness in 1995 [16].

### 3.2.3.2 Horizontal and Vertical Field of View — Confirmed, Partial Viewports



**Figure 7: Virtual Field of View and Real Field of View Ratios**

The field of view (FOV) factor includes the actual screen's field of view and the ratio of the real screen to the virtual rendering plane. The actual screen's field of view and the virtual rendering plane are called the *real* field of view and *virtual* field of view, respectively. The effect of variations in the real field of view is well supported, but research on the ratio of the real versus virtual field of view is conflicted. Figure 7 provides examples of a magnifying one-to-two condition (a), a one-to-one ratio (b), and a minifying two-to-one condition (c).

Generally, only the physical horizontal or diagonal field of view dimension is given. This is because the vast majority of displays have 4:3 or 16:9 ratios. *Seay et al.* reported that the SSQ-T score was higher for a near 180° field of view than for a 60° field of view, even when not controlling for level of user control and stereoscopic/monoscopic viewing [105]. *Duh et al.* found similar results when testing 30°, 60°, 90°, 120°, 150°, and 180° conditions in two virtual environments (a city and a black and white radial pattern) [106]. For both scenes, increases in the size of the field of view generally resulted in significant increases in cybersickness. There was no statistical difference in the ratings between the scenes. *Harvey and Howarth* examined

this effect with small (39 inch), medium (70 inch), and large (230 inch) screen sizes with identical luminance for each condition [45], and found that sickness ratings increased with screen size. *Dizio and Lackner* reported that halving the field of view also halved the symptoms of cybersickness, although the exact values were not reported [101]. *Ujike, Yokoi, and Saida* also reported that increasing screen size increases illness, but no statistical analysis was performed [58]. *Stoffregen et al.* studied video games, and reported a similar doubling effect [30].

An examination of the above data shows that doubling the field of view approximately doubled the severity of cybersickness in each study. The actual values are shown in Table VIII. *Harvey and Howarth's* study is not included because there was no method to convert their *malaise score*, which ranged from 1-4, to an SSQ-T estimate. All the non-SSQ values were transformed to SSQ-T values for comparison in the chart in Figure 8. To use the results of *Toet et al.* and *Duh et al.*, the MISC and difficulty scores had to be converted to SSQ-T values. Because they did not report SSQ values, it was impossible to calculate a direct estimate using their results. *Keshavarz and Zschutschke's* fast motion sickness (FMS) scale is very similar to the MISC scale, but has a different constant that ranges from 0 to 20 [82]. Therefore, to convert the MISC scale the MISC values were multiplied by two and then by the average FMS to SSQ-T scaling factor. The difficulty scores were given the same multiplier since difficulty scores has the same scale as the MISC. Estimating field of view effects presents the same problem as habituation in that the starting values may vary dramatically and have a strong effect on the results due to changes in the field of view.

Table VIII: FOV Values

|                | <b>Study</b>                           |                                             |                                               |                               |
|----------------|----------------------------------------|---------------------------------------------|-----------------------------------------------|-------------------------------|
|                | <i>Seay et al. [102]</i>               | <i>Duh et al. [106]</i>                     | <i>Toet et al. [69]</i>                       | <i>Stoffregen et al. [73]</i> |
| <b>Measure</b> | <i>SSQ-Horizontal FOV</i>              | <i>Difficulty maintaining posture(1-10)</i> | <i>MISC (0-10) (real to virtual FOV)</i>      | <i>SSQ (standing only)</i>    |
| <b>FOV</b>     |                                        |                                             |                                               |                               |
| <b>30</b>      |                                        | 2, 1.5                                      | 3.25 (1-1), 1.5 (1-2)                         |                               |
| <b>35</b>      |                                        |                                             |                                               |                               |
| <b>43</b>      |                                        |                                             |                                               | 60                            |
| <b>60</b>      | 13.2 (N), 17.1 (O), 11.14 (T for mono) | 2.5, 2.5                                    | 4.25 (1-1), 1.1 (2-1)                         |                               |
| <b>77</b>      |                                        |                                             |                                               | 100                           |
| <b>90</b>      |                                        | 3.5, 4.5                                    |                                               |                               |
| <b>120</b>     |                                        | 4.5, 6.1                                    |                                               |                               |
| <b>150</b>     |                                        | 5, 7                                        |                                               |                               |
| <b>180</b>     | 30.8 (N), 31.7 (O), 28.19 (T for mono) | 5.3, 7.5                                    |                                               |                               |
|                | <b>Study</b>                           |                                             |                                               |                               |
|                | <i>Ujike, Yokoi, and Saida [104]</i>   | <i>Lin et al. [105]</i>                     | <i>Kershavarz, Hecht, and Zschuschke [96]</i> | <i>Ours 1</i>                 |
| <b>Measure</b> | <i>SSQ</i>                             | <i>SSQ non transformed-horizontal FOV</i>   | <i>FMS (0-20)</i>                             | <i>SSQ</i>                    |
| <b>FOV</b>     |                                        |                                             |                                               |                               |
| <b>13</b>      | 3                                      |                                             |                                               |                               |
| <b>19</b>      | 3.9                                    |                                             |                                               |                               |
| <b>28</b>      | 4.5                                    |                                             |                                               |                               |
| <b>35</b>      |                                        |                                             | 4                                             | 27.268                        |
| <b>43</b>      | 8.9                                    |                                             |                                               |                               |
| <b>60</b>      |                                        | 0.47                                        | 9                                             |                               |
| <b>77</b>      |                                        | 0.82                                        |                                               | 37.24                         |
| <b>90</b>      |                                        |                                             |                                               |                               |
| <b>100</b>     |                                        | 1.49                                        |                                               |                               |
| <b>180</b>     |                                        | 1.65                                        |                                               |                               |

<sup>1</sup>The results are based on stereo rendering and screen size experiments.

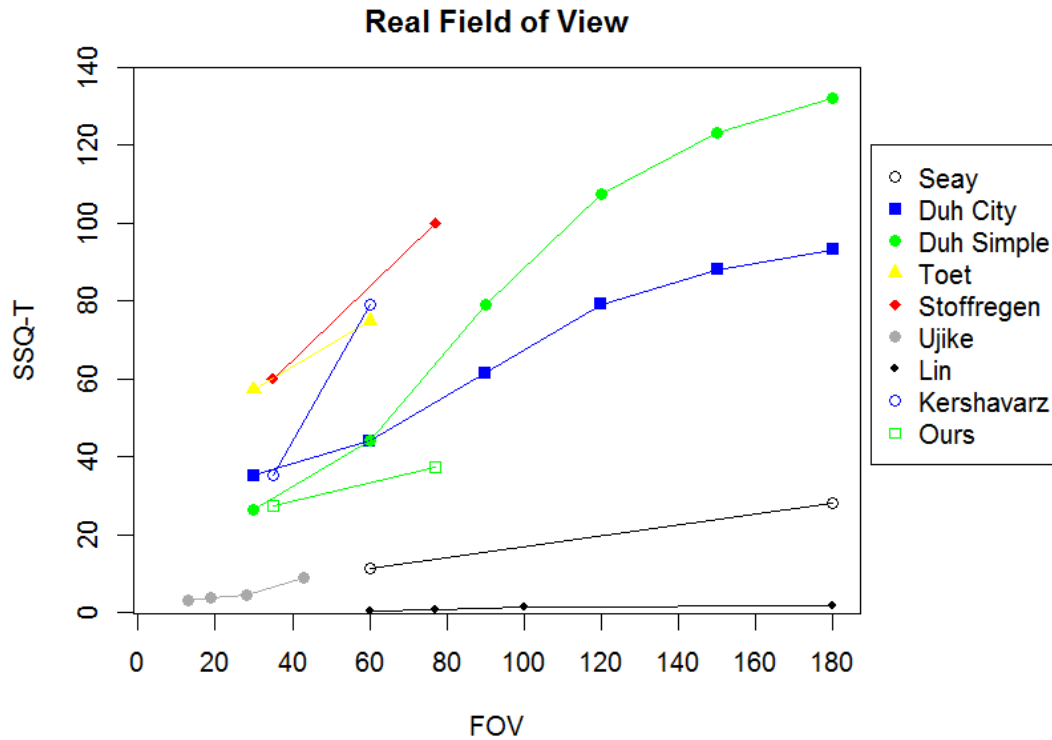
Therefore, when developing the model, the target data used was the percent change in the effect given the initial field size and the difference in the screen size. The data points within a study were paired with every other data point within the study. The resulting plane is shown in Figure 9 and can be expressed using the following formula:

$$FOV(A, B) = 1.44 (b_{FOV} - a_{FOV}) - .45a_{FOV} + 40.49$$

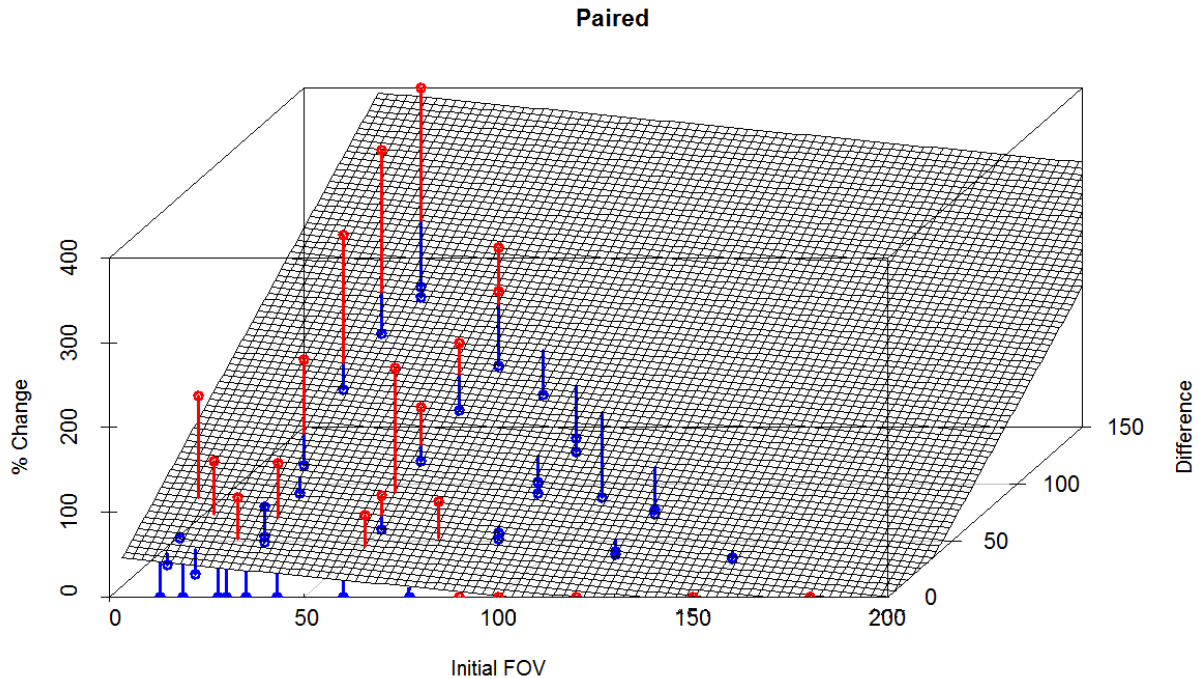
3

*Where  $b_{FOV} \geq a_{FOV}$*

Where  $A$  and  $B$  are virtual environment configuration factor vectors, and  $a_{FOV}$  and  $b_{FOV}$  are their diagonal fields of view. For clarity, the points above the plane are shown in red, while the points below the plane are shown in blue.



**Figure 8: Real Field of View Data**



**Figure 9: Percent Change in SSQ-T with Change of FOV**

The effect of the ratio between the real and virtual fields of view is less clear. Until recently, researchers had assumed that a one-to-one ratio was ideal. *Draper et al.* had reported that a two-to-one real-to-virtual field of view ratio resulted in increased cybersickness symptoms when compared with the standard one-to-one ratio. *Toet et al.* were the first to propose that a ratio that is not one-to-one might improve cybersickness symptoms [71]. They altered the field of view ratio of a projection screen by altering the viewing distance, and reported that a one-to-one ratio was associated with a higher severity of cybersickness versus other ratios. They found a significant increase in sickness ratings using both minifying and magnifying conditions. *Moss and Muth* reports a conflicting result, having found no cybersickness effects that were due to the ratio between the real and virtual field of views [29]. *Van Emmerik, de Vries, and Bos* argue that divergent results on the correct ratio may be primarily due to variations in the real field of

view. Their smallest field of view (40°) was larger than *Draper et al.*'s largest field of view (25°). Given the demonstrated doubling effect of the real field of view, the effect could have been masked. In addition, *Draper et al.* employed a panorama image for their environment that lacks the foreshortening and object occlusion of most virtual environment experiments. *Moss and Muth's* ratios were smaller than those of *Van Emmerik, de Vries, and Bos* or *Dizio and Lackner* and included different peripheral occlusions. They did not find an interaction between the rendering ratio and peripheral vision, but their results may have been impacted by a high dropout rate and a change in the procedure midway through the study.

#### **3.2.3.3 Weight of the Display — Possible**

The weight of the display has been assumed to be a source of increased symptoms in an HMD, but very few empirical investigations of its effects on cybersickness have been conducted. Only one study was found that considered the weight of the display, and the conclusion was that it had no effect on cybersickness [101]. However, it was used as a secondary component and no statistics were reported. Therefore, the weight of the display was included in our experiment set. Subsequent analysis showed that the display weight had no effect on cybersickness, so the *possible* label was changed to *unlikely* after experimentation.

#### **3.2.3.4 Display Type — Probable**

The literature and anecdotal evidence suggests that the display or screen used has an effect on cybersickness. In contradiction, the effects in one system are also assumed to occur in a different configuration. Cybersickness researchers have consistently reported increased effects in the progression from desktops to large screens to HMDs, although the differences may not be significant. Anecdotally, although desktop applications are associated with decreased



cybersickness, *Vinson et al.* showed that cybersickness can occur with desktop virtual reality applications [107].

*Sharples, Cobb et al.* compared four display systems: HMD, desktop, projection (large screen), and reality theatre [108]. All four systems resulted in measureable incidences of cybersickness. They found that the HMD produced higher SSQ-N scores than the other three systems, and that the HMD's SSQ-T and SSQ-D scores were higher than those of the desktop system. The projection screen and reality theater systems had similar results. Although there was not a significant difference between them, their SSQ-T values were distributed between the desktop and HMD SSQ-T values. *Liu and Uang* compared a standard monitor, a stereoscopic monitor, and an HMD with the addition of varying depth cues [109]. Depth cues are pieces of visual information that allow participants to estimate the distance and size of objects. The HMD produced higher cybersickness scores than a conventional monitor.

*Smart, Otten, and Stoffregen* reported on the percentage of participants that become ill using different displays [20]. In a moving room, 23% of them became ill, in a space travel simulator, 43% of them became ill, with a projector system, 17% of them became ill, and with an HMD, 42% percent of them became ill. All the experiments included the same sinusoidal motion, but the visuals used were variable.

One difficulty that is encountered when analyzing the results of different displays is that other factors tend to shift with the different displays, which confounds the analysis. A projection screen allows a participant to see the real world next to a display which mimics an independent visual background. Most projection systems also require a person to stand, while most HMDs

and most monitors do not have this requirement. HMDs also typically have smaller real fields of view and different resolutions. *Kershavarz, Hecht, and Zschutschke* held many of these factors constant [82]. Initially, participants viewed the same stimuli on an HMD and a large screen with the same visual angles and chin rest. The large screen induced higher symptoms than the HMD, which is in direct conflict with several of the studies that were presented earlier. To try to determine the source of these differences, they mimicked an HMD's view by masking the view to just the projection screen, so that the external environment could not be seen. This experiment revealed no difference in cybersickness symptoms between the masked screen and the HMD. Therefore, if external factors are held constant, there is no difference in cybersickness symptoms between displays if no tracking is provided. Our experimentation later supported *Kershavarz, Hecht, and Zschutschke's* claim that the display itself has little effect, and instead the differences lie elsewhere. Therefore, this factor was relabeled as *unlikely* after experimentation.

### **3.2.4 Non Visual Feedback**

The non-visual stimuli in virtual environments are rarely studied. Sound, olfactory, and haptic feedback may increase the realism of a system, but there has been a lack of research on these topics. Ambient temperature may be a concern as it impacts the comfort of the participants.

#### ***3.2.4.1 Type of Haptic Feedback — Untested***

Haptic feedback can increase the realism of a virtual environment. Because more natural types of movement ease cybersickness symptoms, the inclusion of haptic feedback may also help decrease cybersickness. No studies directly relating haptic feedback and cybersickness were

found in the literature. However, studies in position (sitting versus standing) suggest that increased tactile feedback decreases symptoms.

#### ***3.2.4.2 Ambient Temperature —Untested***

Cybersickness can cause sweating, so participants are often more comfortable in cooler environments. Virtual reality labs are typically air-conditioned, but HMDs produce a small amount of warmth. Those with motion sickness often desire cool air upon the onset of their symptoms, but ambient temperature has shown to have no effect on the incidence of motion sickness [110]. However, sweating often proceeds motion sickness and may therefore be an effective warning symptom [111].

#### ***3.2.4.3 Olfactory Feedback —Untested***

Olfactory feedback is rare in virtual environments, but there are olfactory hardware under current development [112]. In all likelihood, including scents that would make people nauseated in the real world would make them nauseated in the virtual world, but no studies have been performed based on this assumption.

#### ***3.2.4.4 Audio Feedback —Untested***

Sound can be easily added to most virtual environments. Headache-inducing sounds would likely increase cybersickness, but no research regarding this factor was found in the literature.

### **3.3 Software**

The application may have a substantial effect on cybersickness. An application that places all of the required objects immediately in front of a participant is very different from one that requires the participant to wander through the environment. The SSQ values reported solely for head mounted displays range from 6 [36] to 120 [113]. Software factors tend to be harder to

quantify. If a participant has free control over their interaction in the environment, the visual stimuli may vary considerably in the same application. Therefore, many studies of software aspects use a chin rest to ensure consistent visual stimuli. Unfortunately, this also creates some uncertainty of the effect of the software when the results are applied to systems that allow free movement.

### **3.3.1 Movement**

Movement is the most studied aspect of virtual software as most applications require some interaction with the environment. The speed of this interaction is well correlated with cybersickness, although its limits are less certain. The expectation of movement is also correlated with cybersickness, where participants having more control over their motion exhibit less cybersickness.

#### ***3.3.1.1 Rate of Linear or Rotational Acceleration —Untested***

Acceleration in a virtual environment is either controlled by the application or by the participant through the use of some sort of controller. When the acceleration is controlled by the application, it is easy to adjust the starting and stopping accelerations. When it is controlled by the user, the acceleration may be very dramatic, and may even contain instantaneous stopping and starting. The effects of frequent changes in acceleration have been well studied, and are discussed in greater detail below. The amount of acceleration may also have an effect on cybersickness. There are currently no cybersickness studies in the literature on the acceleration factor; however, studies on seasickness have presented models based on frequency and acceleration. Increased illness is reported with moderate frequencies, but

increasing the acceleration increases illness at all levels [114,115,116]. This effect is illustrated below in Figure 10.

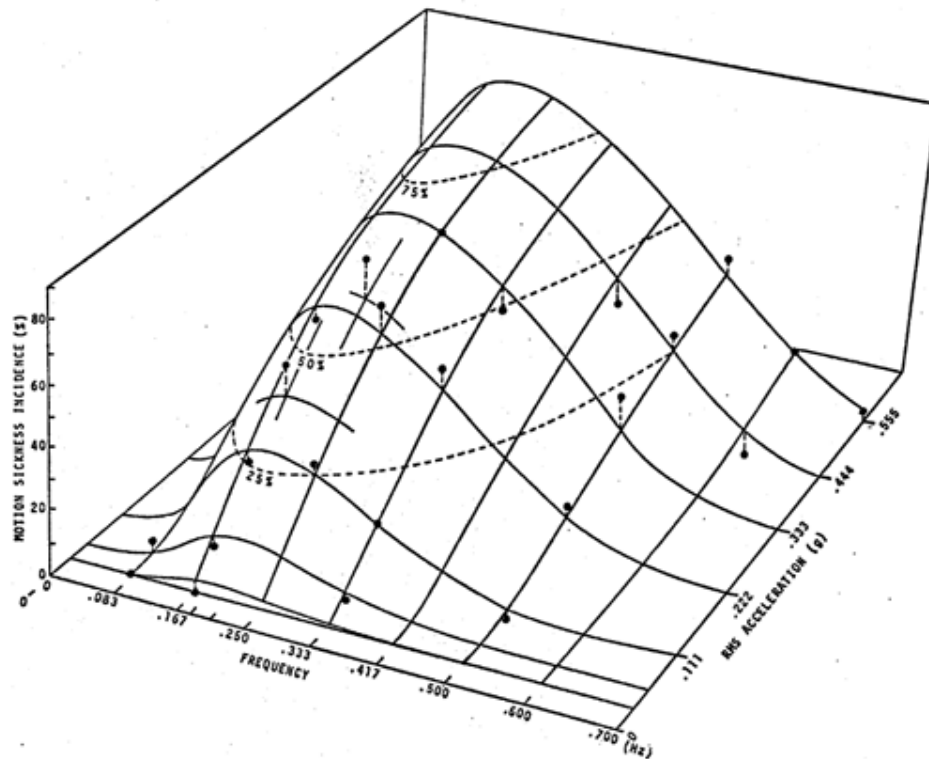


Figure 10: Seasickness Model from McCauley et al. [116]

### 3.3.1.2 Self-Movement Speed and Rotation —Confirmed, Partial

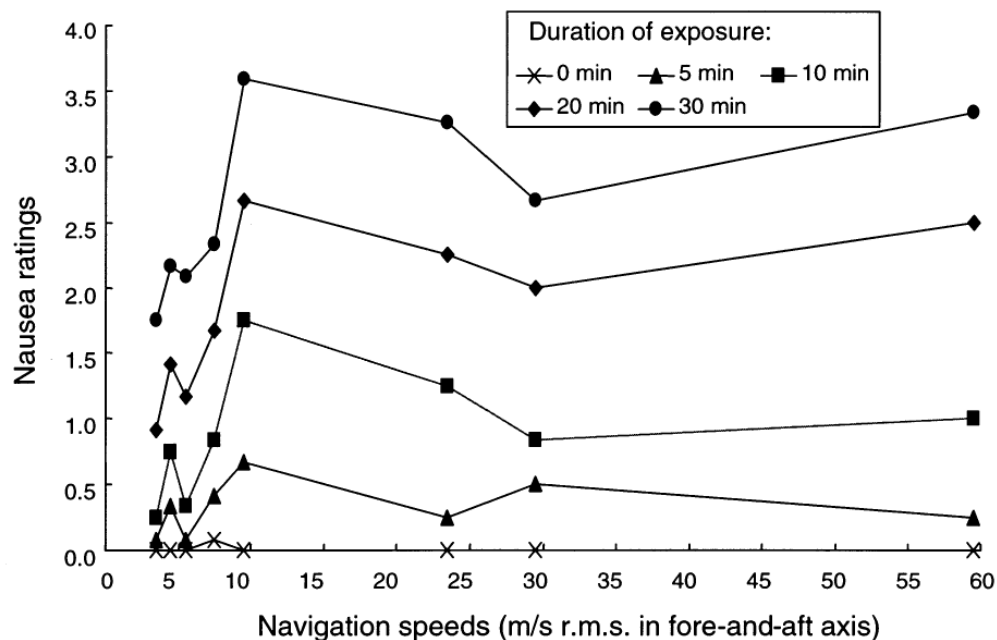
Although the acceleration within a virtual environment has not been tested in cybersickness studies, movement velocity has generated substantial interest in the field. Simply showing a picture to a participant in a virtual environment does not cause cybersickness [117,118]. Therefore, it is clearly movement through the world that induces symptoms. There have been several studies on translational and rotational movement that have attempted to ascertain the speed boundaries that might be associated with a significant decrease in cybersickness symptoms. Anecdotally, cybersickness decreases when the translational speed is sufficiently slow or sufficiently fast to blur the scene. However, due to limits on refresh rates and

implementations of motion blur, no studies have found a maximum speed associated with a decrease in cybersickness.

To assure consistent speed through the environment, and therefore the presented visual stimuli, most studies of navigation speed are done with a chin rest. Studies have shown that it is not necessarily the direction of movement that is the source of the problem. *Chen, Chen, and So* presented a cave scene to their participants with identically textured walls, and then moved the viewpoint along the vertical, horizontal, and fore-aft axes [119]. No single axis was found to be worse than the others.

*So, Lo, and Ho* considered the effect of navigation speed in the Z axis [77]. They tested 8 conditions of forward navigation: 3.3, 4.3, 5.9, 7.9, 9.5, 23.5, 29.6, and 59.2 meters per second. The same video was displayed to participants at different speeds. The speeds of the other axes were proportional to the forward translation speed. The resulting SSQ-T values are presented in Figure 11. Increasing the forward speed steadily increases cybersickness, but duration eventually masks this effect. A high dropout rate likely affected the results in Figure 11. Using a repeated-measures analysis, they showed that duration had an effect from 10 m/s to 30 m/s. *Mourant and Thattacheny* tested the effects of driving at 25 mph in a city, 60 mph in a rural setting, or 60 mph on a highway [120]. Although they used an actual vehicle as a control, the visuals were rendered with an HMD. All the conditions exhibited a significant increase in cybersickness, but the 60 mph condition was associated with a smaller increase than the 25 mph condition. Unfortunately, this difference may have been due to either a difference in speed or visuals. Upper bounds on speed have not been firmly established. The visual blur that

is assumed to decrease cybersickness could not be analyzed in the above studies due to the refresh rate used, as a refresh rate of 60 Hz or higher is theoretically required for blurring to occur without implementing motion blur in the program. With actual video, the time span that is required to create each frame creates motion blur, while in computer rendering it is instantaneous, which prevents blur in the absence of additional rendering features. Motion blur can be implemented in the applications, but it is rarely done.



**Figure 11: Nausea versus Navigation Speed from So, Lo, and Ho [77]**

So proposed the Cybersickness Dose Value (CSDV), which is defined as the integral of “spatial velocity” over time multiplied by display, task, and individual scaling factors [10]. The scaling factors were later dropped [15]. So, Ho, and Lo subsequently defined their measure of scene complexity using the luminance frequency along the horizontal, vertical, and radial axes, and navigation speed [15]. They found a correlation between spatial velocity and cybersickness

symptoms when they increased the scene velocity in the Z axis with yaw rotation. In our own studies, the participants commented that using the *run* button induced cybersickness.

Rotation is often considered independently to limit possible correlations with other navigation modalities. In cybersickness research, there is no agreed upon “dominant” single axis of rotation that causes an increase in illness. *So and Lo* considered pitch, yaw, and roll axis rotations [78]. While the SSQ-N scores increased for all the axes versus no rotation, no one axis was worse than the others.

*Duh et al.* examined roll axis rotation with oscillating frequencies of 0.05, 0.1, 1.2, 0.4, and 0.8 Hz in two virtual environment scenes [121], a tropical hillside scene and a black and white radial pattern. The cybersickness score increased as the frequency decreased in both virtual environments, and the 0.8 Hz rotation condition showed no statistical difference from the baseline. They then extended the experiment to include physical motion. In their second experiment, they rotated the individual in the same axis as the visual stimulus, although not at the same frequency. The resulting perceived frequency was 0.2 Hz or 0.06 Hz on average. They found the sickness ratings to be significantly higher for the 0.06 Hz average rotation. *Chow et al.* examined oscillating frequencies of 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 Hz and found that cybersickness symptoms decreased with increasing frequency, but no formal statistics were reported [122]. *Chen et al.* presented a checkerboard tunnel to participants and oscillated the scene to imply forward motion at specific luminance frequencies [123]. They tested 0, 0.05, 0.1, 0.2, and 0.8 Hz frequencies with the velocity held constant and found a significant difference



between 0.05 and 0.8 Hz for vection ratings, with 0.8 Hz having a lower score. This is similar to navigation speed in that excessive movement decreases cybersickness.

The effect of rotation is worsened if the rotation occurs over more than one axis. *Bonato, Bubka, and Palmisano* examined simultaneous multiple axis rotations [124]. A checker board room was presented to their participants along with a stationary virtual frame. They then oscillated the room around one or two axes. They found higher cybersickness ratings under the two axis rotation condition. *Keshavarz and Hecht* further explored the effects of multiple rotation axes [83]. They created a virtual rollercoaster with pitch, pitch and roll, or yaw, pitch and roll conditions. The cybersickness symptoms increased during the pitch-only condition, but slowed after approximately five minutes. The multiple axes conditions resulted in more cybersickness.

In all likelihood, translational and rotational speed affect cybersickness, but more studies are needed to firmly establish the patterns of this effect. Also, while rotation studies and sea sickness studies are fairly consistent, most applications do not present continual rotation. The variance, axes, and average speed may be needed for a complete model, but most applications have most of their motion in 1 to 3 axes. Therefore, using only the axes with the highest amounts of motion may be an acceptable estimate for modeling. The models created here are tentative. The values reported from the above studies are shown in Table IX.

*Mourant* reported their results as SSQ-O rather than SSQ-T values. To allow a model to use their results, SSQ-O must be converted to SSQ-T values. Because they used a visual similar to *So, Lo*,

and Ho, their overlapping conditions should have similar SSQ-T values. Therefore, Mourant's 25 mph condition was estimated as the average of So's studies at 9.5 m/s (21 mph). The remaining SSQ-O values were scaled proportionally. The resulting model is shown in Figure 12, where  $a_{mph}$  is the forward translation speed in miles per hour. As there are only a few data points, this formula is tentative:

$$Speed(A) = 11.17 + 2.56 a_{mph} - 0.38 a_{mph}^2 \quad 4$$

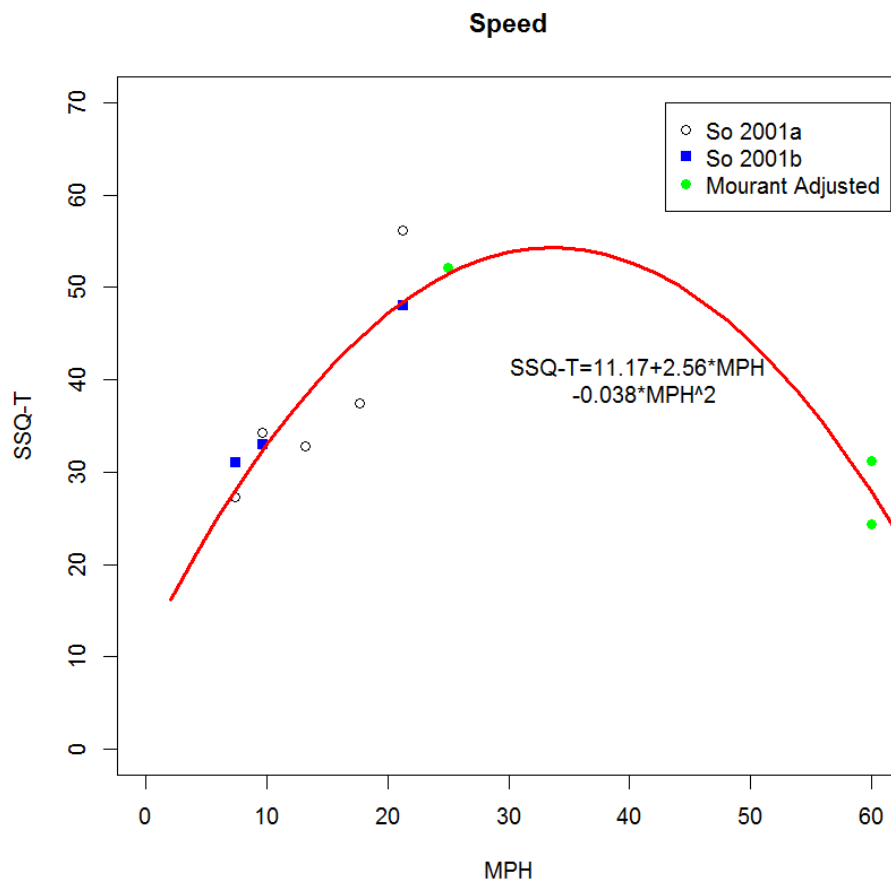
**Table IX: Speed Values**

|                | <b>Study</b>                           |                                      |                                        |
|----------------|----------------------------------------|--------------------------------------|----------------------------------------|
|                | <i>So, Lo, and Ho [77]<sup>1</sup></i> | <i>Mourant and Thattacheny [120]</i> | <i>So, Ho, and Lo [15]<sup>2</sup></i> |
| <b>Measure</b> | <i>Nausea ratings (0-6)</i>            | <i>SSQ-O</i>                         | <i>SSQ-T</i>                           |
| <b>Speed</b>   |                                        |                                      |                                        |
| <b>3.3 m/s</b> | 1.75                                   |                                      | 31                                     |
| <b>4.3 m/s</b> | 2.2                                    |                                      | 33                                     |
| <b>5.9 m/s</b> | 2.1                                    |                                      |                                        |
| <b>7.9 m/s</b> | 2.4                                    |                                      |                                        |
| <b>9.5 m/s</b> | 3.6                                    |                                      | 48                                     |
| <b>25 mph</b>  |                                        | 15                                   |                                        |
| <b>60 mph</b>  |                                        | 7 highway, 9 rural                   |                                        |

<sup>1</sup> Only up to 10 ms were recorded because dropout and duration may have affected the results above that threshold.

<sup>2</sup> This is from the same experiment as So, Lo, and Ho [77], but uses a different measure.

Because rotation studies have examined frequency rather than velocity, only general suggestions can be inferred from them. Rotation speed should be either extremely slow or moderately fast. Very high speeds are unlikely to have an effect. The caveat is that jittering the display also tends to anecdotally increase cybersickness symptoms. These frequencies would be well above what was tested, but are inferred to have an effect in Kiryu *et al.*'s study [125].



**Figure 12: Fitted Speed Values**

### ***3.3.1.3 Vection —Conflicted***

Vection is the participant's feeling that the environment is moving away from oneself. Previous research has suggested that vection is correlated with cybersickness, and vection is commonly cited as the reason why wide screen displays increase cybersickness [126,127]. This also explains why static imagery has little effect on cybersickness [117]. *Hettinger, Berbaum, and Kennedy* indicated that participants who reported vection were much more likely to report feelings of motion sickness [126]. They did not find a linear effect, and therefore used a dichotomous "yes or no." *Webb and Griffin* reported a less clear relationship [127]. The illness

ratings of the high and low vection conditions were similar. *Ji, So, and Cheung* reported that illness can still occur in the absence of vection [128]. The main issue with vection in cybersickness research is that it relies on participant reports because there is no objective measurement of vection. At best, this implies that backwards motion should be limited to decrease cybersickness symptoms.

#### ***3.3.1.4 Altitude above Terrain —Probable***

In flight simulator research, the altitude above the terrain can dramatically affect what is seen. In cybersickness research, *Watanabe and Ujike* compared walking on the ground (a hilly condition) with a planar fly-over of a hilly virtual environment [43]. *Watanabe and Ujike* found an increase in the SSQ-D score for the height-varying mode over the planar fly-over condition, but the SSQ-T scores were statistically identical. The fly-over condition had the effect of flattening the environment, which has been suggested to decrease cybersickness. *Golding, Doolan et al.*'s initial environment conditions were flat environment with an upright, inverted, and abstracted scene with no orientation cues. There was no cybersickness effect among these conditions until they included vertical cues in a second experiment [129]. *Taha et al.* performed a pilot study of 10 individuals and reported that taller (higher altitude) participants experienced fewer cybersickness symptoms [95].

#### ***3.3.1.5 Degree of Control —Confirmed***

Research supports the seemingly obvious notion that shaky motion is more likely to induce cybersickness than smooth motion. Shaky motion has been used as a stimulus in cybersickness research [42]. In addition, to intentionally increase the likelihood of illness, a virtually swayed walk may be added [71]. Theoretically, this means that applications should use natural motion

whenever possible, and if applications need to move the camera independently, they should move it in a smooth manner.

*Stanney and Hash* tested three movement conditions: navigation control with active (six degrees of freedom) control, active-passive control (three degrees of freedom with the chosen axes dependent on the given task), and passive (no) control [130]. They reported that all the SSQ category scores for the active-passive condition were lower than the passive control condition. The active condition also produced lower SSQ-O and SSQ-T scores than the passive control condition. *Stanney et al.* considered navigation control alongside the effects of duration, scene complexity, and performance [79], and found that six-degrees of freedom induced higher levels of sickness.

*Dong, Yoshida, and Stoffregen* [91], *Chen et al.* [4], and *Dong and Stoffregen* [90] also considered control in their environment in the most extreme form. That is, if the participant had any control at all. An HMD and a chin rest offered the advantage of guaranteed identical visual stimuli so that recorded scenes from a “driver's” game play could be shown to a “passenger.” In all instances, the passive “passenger” reported higher sickness ratings than the “driver.”

### **3.3.2 Appearance**

The appearance of an application is the hardest cybersickness factor to quantify, particularly if participants are free to roam the virtual world. Global visual flow and scene content/complexity have been the focus of most of the research on this factor. While both of these appearance factors were found to have an effect on cybersickness, there have been few consistent results reported in the literature.

### ***3.3.2.1 Screen Luminance —Untested***

Some researchers have controlled for screen luminance in their research [45] and found that bright systems may cause more eyestrain, or worse, make flicker noticeable. The human flicker threshold decreases with dimmer lighting and, to some extent, color [131]. However, research on the screen luminance factor's effect on cybersickness has not been published.

### ***3.3.2.2 Color —Possible***

The human visual system is more sensitive to certain colors. The most sensitive wavelengths are 530–538 nm (green), which are primarily sensed with the  $\gamma$  cone and partially sensed with the  $\rho$  cone [132]. The least sensitive cone is the  $\beta$  cone, which primarily senses blue. In theory, having a virtual environment primarily composed of a sensitive color could increase eyestrain or the SSQ-O score. The only study on the cybersickness effects of color was done by *So and Yuen* [133]. They found no effects, but only altered approximately one fourth of the scene with two different colors, one of which was a neutral color. There have been reports of a color effect in motion sickness studies, namely, that the inclusion of color imagery increases illness compared with black and white imagery [134]. The human eye also has more difficulty with the extremes of the visual spectrum and with excessively high contrast in text colors and backgrounds [135].

### ***3.3.2.3 Contrast —Untested***

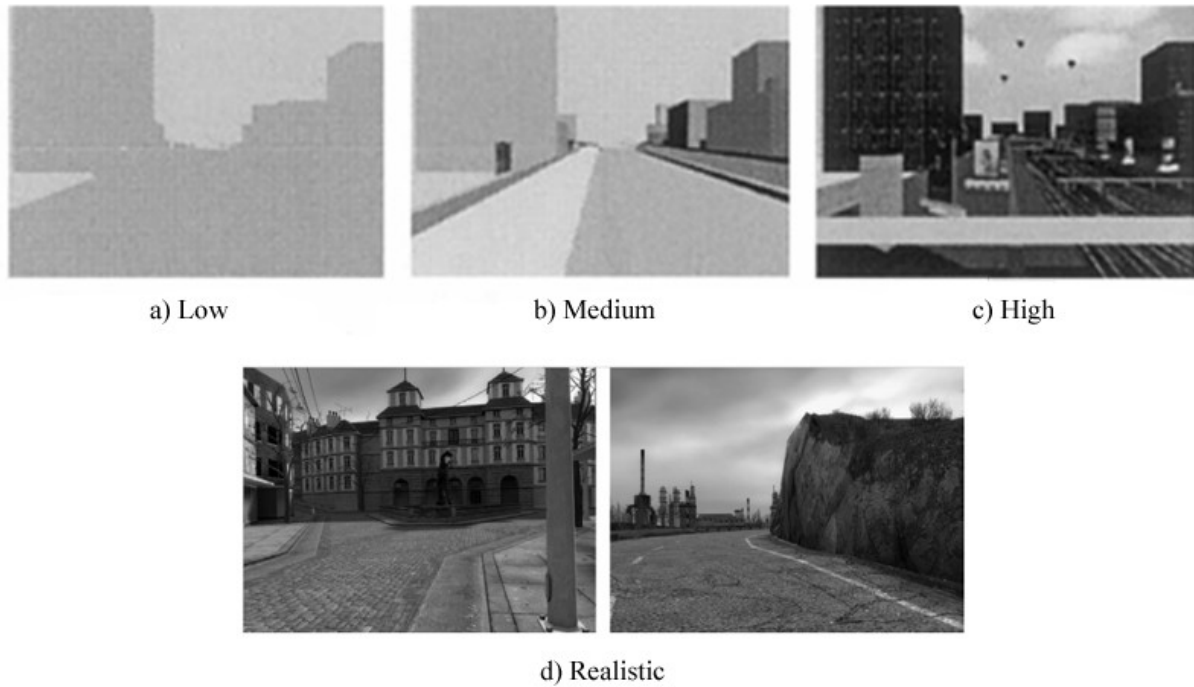
Given the same illumination level, the contrast in natural settings is lower than that of man-made settings, and the contrast in man-made settings is lower than that of typical virtual environments. For example, a park displays varying shades of green while a supermarket may display purple, red, blue, and yellow within a span of a few feet. This increase in contrast can cause extra eye strain; however, the relationship of contrast to cybersickness is unknown.

#### ***3.3.2.4 Scene Content or Scene Complexity —Probable***

Scene content may also affect sickness ratings, but exactly how particular content affects cybersickness is poorly understood. Most studies consider one particular aspect of the content without addressing its relation to the larger system.

*Jaeger and Mourant* considered the level of detail and found a trend of lower SSQ-Ts with lower levels of detail [59]. *Liu and Uang* report conflicting results [109]. They used planar or three dimensional models on shelves with different displays. Their three dimensional model condition produced an increase in cybersickness regardless of the display used, but there were interactions in some of their data.

The fact that cybersickness symptoms decrease with lower levels of detail is similar to the impact of resolution and blur. If a person cannot determine what an image is, there is too little information to cause sensory mismatch. *So et al.* present references for low, medium, and high degrees of scene complexity, as shown in Figure 13 [15]. Low complexity has no textures and presents information about the surrounding environment only. Applications that have only a few objects centered in a blank room also have low scene complexity. In medium complexity systems, there are some textures, and the surrounding environment is clearly 3D. High complexity scenes are mostly textured, but lack shadows and use mostly generic textures. Realistic systems, as illustrated by *van Emmerik, Vries, and Bos* [49], either use actual video or are fully textured with non-generic textures and include shadows.



**Figure 13: Scene Complexity (a-c) from *So et al.* [15] and (d) *van Emmerik, Vries, and Bos* [49]**

### ***3.3.2.5 Global Visual Flow —Probable***

Global visual flow is closely related to scene complexity. Global visual flow is the change in luminance or color of a scene over time. Global visual flow is implicit in rotational and translational speed studies and in realism studies, but only a slight difference between detailed versus black and white imagery has been reported [121]. The Cybersickness Dose Value (CSDV) by So is, in one sense, a global visual flow metric [10][15]. So found a correlation between the CSDV measure and cybersickness symptoms.

### ***3.3.2.6 Orientation Cues —Possible***

One aspect of most virtual environments is that the implied "up" direction agrees with visual and vestibular cues. Orientation cues also affect global visual flow. More highly realistic environments provide more clues about orientation. *Golding et al.*'s pilot experiment used a



panorama that was tilted, inverted, or abstracted to remove any horizontal or vertical cues, and reported no effects based on these conditions [129]. They restructured the conditions so that the visuals consisted of a real scene from Westminster Bridge rather than a perfectly flat landscape, and found that the upright condition induced significantly higher cybersickness symptoms than the inverted condition. They suggest that the inverted condition was likely considered to be so unlikely by the participants that it was not used to determine the "up" direction. Their study also implies that vertical cues are of greater importance than horizontal cues.

Given that their study examined a completely unlikely versus a real environment, their research is inconclusive regarding which orientation cues affect cybersickness.

### **3.3.3 Stabilizing Information**

Stabilizing information has been gaining interest as a cybersickness factor due to some promising results of pilot studies. Independent visual backgrounds, the ability of participants to see part of the real world, or the inclusion of screen stable elements have consistently been shown to decrease cybersickness.

#### ***3.3.3.1 Focus Areas —Probable***

The focus areas factor relates to where a participant should focus in the scene. *Mon-Williams et al.* measured heterophoria during the testing of five different gaze angles, or the vertical angle of gaze relative to the ear-eye line (drawn from the center of the ear to the center of the eye) [136]. The angles were 20° above, and 0°, 20°, 40°, and 60° below the ear-eye line in an HMD. They found that post-immersion heterophoria varied with the gaze angle, with the smallest change occurring at 34° below the center ear-eye line on average, which corresponds closely

with looking directly forward. While there is a fair amount of individual variability, in general, the farther the gaze was from this line, the greater the measured heterophoria.

*Diels, Ukai, and Howarth* also considered whether the focus location on a screen could affect cybersickness symptoms [137]. They displayed a scene consisting of an expanding-contracting random dot pattern oscillating around the center of a screen along the Z axis. When the focus point shifted over time, cybersickness values increased when compared with a static centered focus point or the lack of a set focus point.

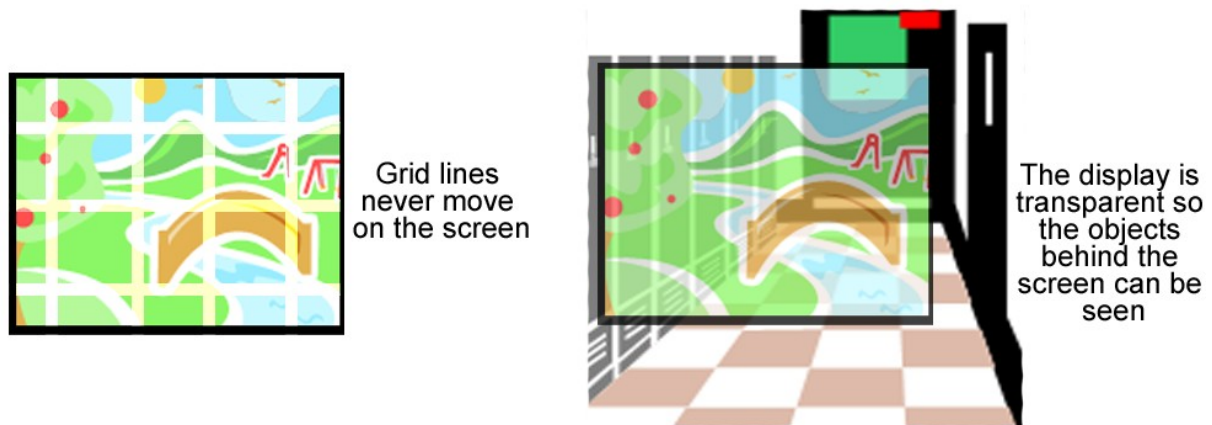
### ***3.3.3.2 Ratio of Virtual to Real World —Untested***

Augmented reality has had almost no reporting of cybersickness, as most of the virtual world is real. The degree to which the world needs to become virtual before cybersickness becomes an issue is unknown. This factor is directly related to independent visual backgrounds, which include parts of the real world in virtual environments.

### ***3.3.3.3 Independent Visual Backgrounds —Confirmed***

Independent visual backgrounds (IVB) are elements of the visual field that remain stable relative to the participant. They may be arranged by either having an object fixed relative to the participant's position on the display or by having an object that is external to the virtual environment yet visible through the display, as presented in Figure 14. IVBs provide a real world expectation that is enforced in relation to the virtual world due to their configurations. The results have been very promising with respect to correlations between IVBs and cybersickness. *Duh et al.* placed a grid at one of three different depths in front of the participant and at two different intensities: bright or dim [138]. The grid improved cybersickness symptom ratings, and there was no difference between the grid conditions except for brightness. In another study by

*Duh et al.*, they tested dim, bright, or invisible grids overlaid on a rotating virtual environment scene at two different frequencies [139]. The grid decreased cybersickness, but there was significant interaction between the grid and the roll frequency. *Moss and Muth* reported that simply removing the peripheral occlusion molding from HMDs decreased cybersickness [29].



**Figure 14: Independent Visual Background**

*Prothero et al.* created an IVB through the use of a partially occluded HMD, in other words, a virtual environment superimposed on the real world [32]. Their first experiment reported lower SSQ-T scores and fewer postural stance breaks under the IVB condition. Their second experiment, which added an identification task to the independent background condition, showed no difference in the SSQ-Ts, but fewer stance breaks were noted under the IVB condition. These conflicting results could mean that the additional focus on the background or the elimination of a participant from part of the analysis had an effect. The median scores on the SSQ were identical in the two studies, but their standard deviations differed.

*Kershavarz, Hecht, and Zschutschke* indirectly tested an IVB by masking a projection screen so that the external environment could not be seen, similar to an HMD [82]. Eliminating the real

world stimuli resulted in the same level of cybersickness using a projection screen and an HMD. These studies imply that even less obtrusive IVBs decrease cybersickness. *Kershavarz, Hecht, and Zschutschke* reported the rather unexpected result that the PowerWall they used induced higher cybersickness symptoms without masking. There are a few possible explanations for this result. An IVB enforces expected stimuli. This is normally the real world, but in very familiar settings such as a virtual car, the IVB enforcing the real world opposes expectations. In addition, different participants were employed in testing the two displays, and they may have had different susceptibilities. The PowerWall had a 3:4 ratio of male to female participants while the HMD had a 15:16 ratio of male to female participants, and females frequently possess higher susceptibility.

Since the IVBs vary dramatically it is difficult to create a model using the IVB factor. The above studies' reported values are shown in Table X. Since an IVB is meant to enforce real world expectations, the values from *Kershavarz, Hecht, and Zschutschke* are "yes" for the HMD and "no" for the PowerWall because the HMD hides the unexpected stable room in a car video.

The average percentage drop was calculated directly without transforming all the measures to the same scale. Since *Duh et al.*'s [103] studies showed no difference across grid conditions, the grid conditions were averaged for the sake of comparison. Since *Prothero et al.* reported the median, which has a different meaning than the mean, only the stance breaks are used in the calculation. In the future, improved models are likely if IVB studies can be combined with "amount of the real world" studies. The average percentage drop in the studies resulting from enforcing the expectation to not enforcing the expectation is 30.6%. If we assume that the

differences in our screen size and HMD studies are due to the IVB effect of seeing the real world, this average drop becomes 30.1%. More formally, where  $a_{IVB}$  is whether configuration  $A$  uses an IVB or not:

$$IVB(A) = \begin{bmatrix} a_{IVB} = \text{"yes"} & 0.699 \\ a_{IVB} = \text{"no"} & 1 \end{bmatrix} \quad 5$$

**Table X: IVB Values**

|             | Study                                           |                                                  |                                       |                                            |                                                  |
|-------------|-------------------------------------------------|--------------------------------------------------|---------------------------------------|--------------------------------------------|--------------------------------------------------|
|             | Duh et al.<br>[138] Bright<br>(Dim)             | Duh et al. <sup>1</sup><br>[139] Bright<br>(Dim) | Prothero et<br>al. [32]               | Moss and Muth<br>[29]                      | Kershavarz,<br>Hecht, and<br>Zschutschke<br>[82] |
| Measure     | Difficulty<br>Maintaining<br>Posture (1-<br>10) | Difficulty<br>Maintaining<br>Posture (1-10)      | SSQ-T<br>median<br>(Stance<br>breaks) | SSQ-T Handrail<br>(SSQ-T, no<br>handrail)  | FMS (0-20)                                       |
| Expectation |                                                 |                                                  |                                       |                                            |                                                  |
| Yes         | 3.2, 2.7, 3.1<br>(3.3, 3.1, 3.8)                | 0.85<br>( 0.9)                                   | 15, 15<br>(4.1, 1.6)                  | 6, 4.8, 4.4, 6.1<br>(5, 3.9, 7, 2.1)       | 3.8                                              |
| No          | 5.1                                             | 1.26                                             | 18.7, 18.7<br>(9.1, 2.6)              | 5.1, 6.6, 8.5, 6.9<br>(5.5, 7.5, 5.4, 8.8) | 9                                                |

<sup>1</sup> A frequency of 0.8 Hz has consistently shown little to no effect on cybersickness in rotation studies, therefore these values were dropped from the model.

### 3.3.3.4 Sitting versus Standing - Confirmed

Some virtual environments are typically used with a standing position while others are typically used in a seated position. This may mask the differences between two configurations. This is one theory behind why monitor configurations are anecdotally associated with less cybersickness. *Merhi et al.* reported a strong cybersickness effect under seating versus standing conditions [140]. All of the standing participants withdrew, but there was no difference in the cybersickness ratings between those that withdrew early under the sitting versus the standing

conditions. Therefore, seating participants should decrease the frequency of cybersickness. Increased tactile information seems to help decrease cybersickness in general. In a study by *Moss and Muth*, the procedure was altered midway to include a hand rail in order to reduce a high dropout rate [29]. *Stoffergen et al.* studied the effect of video games on postural stability and reported the opposite results; their standing participants had lower cybersickness symptoms [30]. Peculiarly, other measures such as mean time to illness and percentage of participants stating illness were slightly worse under the standing condition. Although there are few experiments that specifically examine the sitting versus standing factor, the results are so dramatic that the factor is confirmed, however, the level of experimentation done on sitting versus standing conditions does not permit the modeling of the effect.

### **3.4 Summary of Factors**

The factors that have been shown to be reliable and consistent predictors of cybersickness are listed in Table XI. The factors in this table do not all contain sufficient data to allow for a fitted model, but the literature and experimental results are consistent. Habituation and field of view are special cases in that part of their effect is established, but other components are uncertain. Novel sub-factors have been tentatively relabeled as *possible*. The effect of the horizontal or diagonal screen field of view is well established, but the virtual to real ratio and the vertical fields of view are labeled *conflicted* and *untested*, respectively. Habituation has only been confirmed under the same configurations and applications. Table XIV lists the factors that have no clear indication of effects, and no claims at all can be made of the untested measures listed in Table XV. Of these, the tracking factors are likely to be the easiest to control and merit

further study. While gender has received much attention, its effect may be found though other factors that may have better correlations with cybersickness [65].

The *probable* and *possible* factors are listed in tables Table XVII and Table XVIII, respectively. They lack sufficient data to determine their levels of cybersickness effects. Some of these factors are difficult to determine or control, which limits their usefulness in prediction measures. These factors have been removed and placed into the “elimination” Table XVI. The factors that are difficult to determine or too time consuming for practical commercial configurations are also placed into Table XVI.

Following our experimentation, several factors had their labels altered. A few untested factors were included as experimentation helped to explain conflicting results. For example, the effect of displays was found to be due to other underlying factors. These factors have been placed into their respective tables according to their labels after experimentation.

**Table XI: Confirmed Factors**

| <i><b>Individual</b></i>          | <i><b>Hardware</b></i>   | <i><b>Software</b></i>                |
|-----------------------------------|--------------------------|---------------------------------------|
| <i><b>Experience</b></i>          | <i><b>Screen</b></i>     | <i><b>Stabilizing Information</b></i> |
| Habituation                       | Horizontal field of view | Independent visual backgrounds        |
| Duration                          |                          | Sitting versus standing               |
| Video game play                   |                          |                                       |
| Postural stability                |                          |                                       |
|                                   |                          |                                       |
| <i><b>Physical Attributes</b></i> | <i><b>Tracking</b></i>   | <i><b>Movement</b></i>                |
| History of headaches/migraine     | Method of movement       | Self-movement speed                   |
|                                   |                          | Degree of control                     |
|                                   |                          |                                       |
| <i><b>Demographics</b></i>        |                          |                                       |
| History of motion sickness        |                          |                                       |

**Table XII: Probable factors**

| <i>Individual</i> | <i>Hardware</i> | <i>Software</i>                   |
|-------------------|-----------------|-----------------------------------|
|                   |                 | <i>Movement</i>                   |
|                   |                 | Altitude above terrain            |
|                   |                 |                                   |
|                   |                 | <i>Appearance</i>                 |
|                   |                 | Scene content or scene complexity |
|                   |                 | Global visual flow                |
|                   |                 |                                   |
|                   |                 | <i>Stabilizing Information</i>    |
|                   |                 | Focus area                        |

**Table XIII: Possible Factors**

| <i>Individual</i>                          | <i>Hardware</i>                        | <i>Software</i>                |
|--------------------------------------------|----------------------------------------|--------------------------------|
| <i>Experience</i>                          | <i>Screen</i>                          | <i>Appearance</i>              |
| Experience with other virtual environments | Resolution/Blur                        | Color                          |
|                                            | Ratio of real to virtual field of view | Orientation cues               |
|                                            | Vertical field of view                 | Self-movement rotation         |
|                                            |                                        |                                |
| <i>Demographics</i>                        | <i>Tracking</i>                        | <i>Stabilizing Information</i> |
| Age                                        | Position tracking error                | Ratio of virtual to real world |
|                                            |                                        |                                |
|                                            | <i>Rendering</i>                       |                                |
|                                            | Inter-pupillary distance               |                                |

**Table XIV: Conflicted Factors**

| <i>Individual</i>               | <i>Hardware</i>        | <i>Software</i> |
|---------------------------------|------------------------|-----------------|
| <i>Experience</i>               | <i>Tracking</i>        |                 |
| Experience with real-world task | Tracking method        |                 |
| Vision correction               | Stereoscopic rendering |                 |



**Table XV: Untested Factors**

| <i>Individual</i>   | <i>Hardware</i>            | <i>Software</i>                           |
|---------------------|----------------------------|-------------------------------------------|
| <i>Demographics</i> | Tracking                   | Movement                                  |
| Ethnicity           | Calibration                | Rate of linear or rotational acceleration |
|                     | Head movements             |                                           |
|                     |                            |                                           |
|                     | <i>Non Visual Feedback</i> | Appearance                                |
|                     | Type of haptic feedback    | Screen luminance                          |
|                     | Ambient temperature        | Contrast                                  |
|                     | Olfactory feedback         |                                           |
|                     | Audio feedback             |                                           |

**Table XVI: Eliminated Factors**

| <i>Individual</i>          | <i>Hardware</i>            | <i>Software</i> |
|----------------------------|----------------------------|-----------------|
| <i>Experience</i>          | <i>Screen</i>              | <i>Movement</i> |
| Hats                       | Weight of display          | Vection         |
|                            | Display type               |                 |
|                            |                            |                 |
| <i>Physical Attributes</i> | <i>Rendering</i>           |                 |
| Eye dominance              | Update rate                |                 |
| BMI                        | Screen distance to the eye |                 |
|                            |                            |                 |
| <i>Demographics</i>        |                            |                 |
| Gender                     |                            |                 |
|                            |                            |                 |
| <i>Mental Attributes</i>   |                            |                 |
| Mental rotation ability    |                            |                 |
| Concentration level        |                            |                 |
| Perceptual style           |                            |                 |

## **4 General Procedure and Hypotheses**

A detailed examination and summarization of the literature allowed us to prioritize cybersickness factors. However, it also revealed some discontinuities in the existing cybersickness knowledge. Individual susceptibility has not been well considered in cybersickness research, and there are several conflicting or ambiguous factors. For this reason, we conducted a series of experiments, including a search for individual factors and a clarification of display factors, while holding known factors constant. These results were then combined to create predictive models as a means to compare the results across different virtual reality systems and develop future guidelines. The sets of experiments we performed include HMD weight (Our HMD), screen size (Our Screen), and stereoscopic rendering (Our Render).

Anecdotally, the weight of an HMD is assumed to increase cybersickness. Modern displays range in weight from 220 grams (eMagin 3 Visor) to 440 grams (Oculus Rift). The center of gravity of the head is altered, since the weight is primarily in front of the display, and the tightness of the bands may cause headaches [75,76]. Only one study was found in the literature that took HMD weight into consideration [101]. The study found no effect on cybersickness, but given that its focus on HMD weight was secondary and the lack of reported statistics, the effect of this factor remains uncertain. The HMD weight experiment we conducted directly considered this factor.

Conventional desktop monitor displays have been associated with a trend of decreased cybersickness compared with other types of displays [108,109]. At a fundamental level, there is little difference between a monitor and a large screen display. Both are flat, stationary displays

that can use a nearly identical interface. In practice, there are several differences. Large screens usually have larger fields of view and typically engage standing participants, while participants are usually seated in front of monitor displays. Other common differences include ambient lighting, angular momentum, resolution, head tracking, and refresh rate. The screen size experiment directly considered this factor.

From the first two experiments, we concluded the differences reported between display types are not due to the weight of the display or the size of the screen. The remaining question was if there would be a change in cybersickness between a large screen and an HMD when participants are standing and had the same average field of view in both. There are a few fundamental differences between these displays. An HMD blocks out the outside world making the scene appear to float in space, while the room is still visible to the participant with a large screen. This may yield an IVB-like effect. The interaction also differs slightly. An HMD alters the rotation of the view with head movements, while head tracking for large screens adjusts the display frustum, but not the rotation. This was considered in the display type's analysis.

Most studies of stereoscopic rendering use eye strain or heterophoria as a measurement. However, the stereoscopic rendering effect is highly individualized, and the extent to which heterophoria encompasses cybersickness is unknown. A quick Internet search for "movie motion sickness" reveals many people complaining of difficulty with 3D movies, so it is reasonable to assume that issue may be transferred to stereoscopic virtual reality. The stereoscopic rendering experiment directly considered this factor.

Cybersickness is known to be highly individualistic and therefore paired statistical tests are preferred in cybersickness studies. Despite this fact, individual demographics and susceptibility are rarely included in cybersickness research. Moreover, the degrees to which individual factors influence cybersickness are largely unknown. If a few questions can determine a participant's susceptibility, they can be used to normalize the cybersickness results across populations, and give a means to dynamically adjust an application to a participant's susceptibility. Several surveys were utilized throughout our HMD weight, screen size, and stereoscopic rendering experiments. These surveys asked for background information from the participants and are explained in further detail below.

#### **4.1 Individual Factors**

To examine individual factors, background surveys were given to all the participants. The surveys are presented in Appendix A. The "usability survey" included both demographic factors and usability factors. A past history of motion sickness, age, and gender were included in Golding's MSSQ [141]. Several questions were specifically designed to address usability. These questions were primarily used to avoid the participants' discomfort due to the display, and to gain insight into the participants' interest in these systems. The self-limiting immersion rating (original usability survey question 9 or revised survey question 7) was included to gain an understanding of a participant's tolerance for cybersickness.

An early analysis of the original usability survey showed that several factors did not meet statistical significance. Thus, they were removed from the revised usability survey. Video game use displayed a trend, and this question was reformatted to gain specific information regarding this trend in the revised usability survey.

**Table XVII. Individual Factors Question Location, Reason, and Hypotheses**

|           | <b><i>Factor</i></b>                                                               | <b><i>Reason for Inclusion</i></b>                                                                                        | <b><i>Hypothesis</i></b>                                                                       |
|-----------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| <b>1</b>  | <i>Hat Use (6<sup>O</sup>)</i>                                                     | Tight band around the head can cause headaches, which may increase cybersickness                                          | Those that wore hats would have a decreased incidence of cybersickness                         |
| <b>2</b>  | <i>Video game use (general) (1<sup>O</sup>)</i>                                    | Video games have similar visual stimuli as virtual environments and therefore create a habituation effect                 | Increased game play will decrease cybersickness                                                |
| <b>3</b>  | <i>Video game use (specific) (1<sup>R</sup>)</i>                                   | Video games displayed a trend and interacted with the MSSQ so clarification was required                                  | Increased game play in certain genres will decrease cybersickness                              |
| <b>4</b>  | <i>Headache/migraine history (2<sup>R</sup>)</i>                                   | <i>Solimini et al. [93]</i> reported a correlation between theater sickness and a past history of headaches and migraines | Those with a history of headaches will be more susceptible to cybersickness                    |
| <b>5</b>  | <i>Vision correction (7<sup>O</sup> and 3<sup>R</sup>)</i>                         | Vision correction adds another layer of refraction and may shift optical placement, increasing eye strain                 | Vision correction will affect cybersickness                                                    |
| <b>6</b>  | <i>Prior use of head tracked virtual reality (2<sup>O</sup> and 3<sup>R</sup>)</i> | Prior use of VR, even in different configurations, may lead to a habituation effect                                       | Those that have previously used VR will have a lower incidence of cybersickness                |
| <b>7</b>  | <i>3d display use (4<sup>O</sup>)</i>                                              | 3D displays have similar visual stimuli as VR and may lead to a habituation effect                                        | Those that have previously often used 3D displays will have a lower incidence of cybersickness |
| <b>8</b>  | <i>Prior 3d display discomfort (5<sup>O</sup>)</i>                                 | Those that have a prior history of issues with 3D displays may be more likely to have trouble with cybersickness          | Those that have had a prior difficulty with 3D displays will have increased cybersickness      |
| <b>9</b>  | <i>Prior history<sup>M</sup></i>                                                   | Being sensitive to one type of motion may increase sensitivity to other types of motion                                   | Those that are more sensitive to motion sickness will be more sensitive to cybersickness       |
| <b>10</b> | <i>Age<sup>M</sup></i>                                                             | Prior studies by <i>Arns and Cern [55]</i> and <i>Park et al. [56]</i> displayed a correlation with age                   | Younger participants will be less susceptible to cybersickness                                 |
| <b>11</b> | <i>Gender<sup>M</sup></i>                                                          | Prior studies include conflicting reports about females having a higher incidence of cybersickness                        | Gender will have no effect when holding MSSQ constant                                          |

During experimentation, *Solimini et al.'s* [93] released a study that examined the relationship of headache and migraine history and symptoms while watching 3D movies, so questions related to those factors were added. The factors under consideration, their reason for inclusion in the surveys, and their associated hypotheses are listed in Table XVII. The original usability survey is labeled with <sup>O</sup> and the revised survey is labeled with <sup>R</sup>. The information from the MSSQ survey is labeled with <sup>M</sup>.

## **4.2 Hardware and Software Factors**

The most problematic of the conflicting factors is the effect of using different displays. All virtual reality systems require the use of a display. Therefore, knowing which displays are more likely to induce cybersickness is critical for creating guidelines. Prior studies have shown trends, but not consistent results relating to the effect of displays on cybersickness. One issue is that several other factors tend to shift with the display. For example, a monitor display is almost always used by a person who is seated, while an HMD is almost always used by a person who is standing. An HMD weighs more than the glasses that are required for 3D monitors or large screen displays. A monitor has a smaller field of view than a large screen display. Standing versus sitting and field of view are both known cybersickness factors with sizable effects.

Stereoscopic rendering has been the subject of considerable study, but most of the results have been reported in terms of eye function rather than cybersickness, and the results are inconsistent. We do not know if heterophoria correlates with cybersickness. Therefore, studies using heterophoria as a measure cannot be directly applied to cybersickness studies.

We completed three sets of experiments to analyze the following factors: HMD weight, screen size, and stereoscopic rendering. The HMD experiment was included to confirm or deny the effect of HMD weight on cybersickness. Anecdotally, the additional weight of HMDs has been blamed for their association with increased cybersickness. In the screen size experiment, the field of view was held constant, and the participants remained standing for both screens, but the average screen size was changed. The field of view was also kept the same as that of the HMD experiments, so the large screen versus HMD analysis could be performed. The final experiment compared bi-ocular with stereoscopic viewing. The field of view was increased and the application was rendered for either stereo or bi-ocular viewing. Bi-ocular viewing was chosen over monoscopic viewing to keep the illumination level constant. Bi-ocular viewing has shown no difference with respect to cybersickness compared to monoscopic viewing [82], so this choice is unlikely to alter the effect. The factors under consideration and their respective hypotheses are available in Table XVIII.

**Table XVIII: Experiments Rational and Hypotheses**

|          | <i><b>Factor</b></i>           | <i><b>Reason</b></i>                                                                                                                                                            | <i><b>Hypothesis</b></i>                                                                             |
|----------|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| <b>1</b> | <i>HMD weight</i>              | Anecdotally, HMD weight has been blamed for increasing cybersickness                                                                                                            | Heavier displays increase cybersickness                                                              |
| <b>2</b> | <i>Screen Size</i>             | Monitors show a trend of decreased cybersickness versus large screens, but other known factors tend to shift with it                                                            | Screen size will have no effect                                                                      |
| <b>3</b> | <i>Display Type</i>            | HMDs are often associated with increased cybersickness. By holding the application, interaction, field of view, and standing position constant, that may or may not remain true | HMDs will increase cybersickness, holding interaction, field of view, and standing position constant |
| <b>4</b> | <i>Stereo versus bi-ocular</i> | Stereo displays tend to cause eye strain, but we do not know how that affects cybersickness                                                                                     | Stereo displays will increase cybersickness                                                          |

### **4.3 Environment**

Testing utilized a virtual environment in the Media and Entertainment Technologies Laboratory.

The virtual environment was presented using Vizard 3.0 with 3-sample antialiasing and a 4:3 aspect ratio. The computer had a 2.58Hz Intel Core 2 Duo E4700, 4GB RAM, and a Quadro FX 3700 graphics card. Tracking was done with an Intersense IS900 which has a specified latency of 4ms. Formal tracker-to-display latency calculations were not performed. If stereo was used, the software IPD was 6 centimeters. Two different display technologies were employed during testing. A Glasstron LDI-D100B HMD, with an 800X600 resolution, fixed interpupillary distance, and a 35 degree diagonal FOV and an stereoscopic capable InFocus DepthQ projector with a maximum resolution of 1600 X 1200 and a maximum of a 120 Hz refresh displayed using a rear-projection screen. The active shutter glasses had a maximum refresh of 100 Hz, and therefore the project was set to a 100 Hz refresh as well.

The test virtual environment consisted of a set of five to nine rooms, two of which were mazes, with objects placed on pedestals or hung on the walls as shown in Figure 15. The game was essentially a treasure hunt for the objects listed on the left-hand side of the screen. Objects and pictures were set to scale, if possible. Participants were timed, but locating a star object removed 30 second from their total time and was counted as an item found. Certain doors were locked and the participants were required to locate a matching colored key to open the door. To ensure progression, the doors unlocked automatically after a specific time period had elapsed.





a



b



c



d



e



f



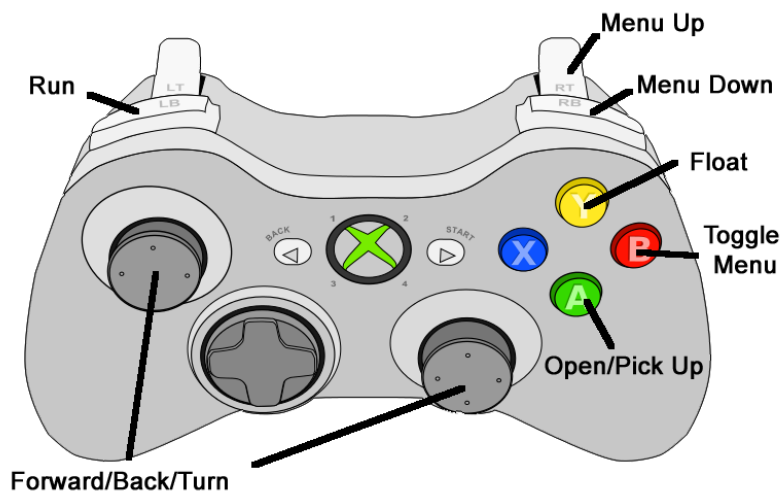
g



h

Figure 15: Screenshots from the Application

To provide navigation help in the mazes, a float button was added to allow the participants to rise 2.5 meters to look over the top of a wall. They could not move forward while they were floating. The normal walk speed was a maximum of 2 m/s and the rotation was a maximum of  $\pi/3$  radians/s. A run button doubled the maximum forward/backward speed. The arrangement of the buttons is illustrated in Figure 16. The head-tracked position and orientation was added directly on top of the controller position and orientation. This means that "forward" was always the same direction in the real world despite how the participant's body was oriented. This encouraged the participants in the HMD conditions to face primarily in one direction and aided in keeping the interactions similar between the HMD and screen experiments.



### Figure 16: X-Box Controls

#### 4.4 Factor Limitations

Certain factors could not be held constant across the studies. The most problematic factor in this regard was habituation. Because cybersickness is highly individualized, different conditions should be tested with the same individual. Unfortunately, due to habituation, a participant's score will naturally decrease from session to session.

The same application was used for all the experiments, but the set of rooms changed from session to session to minimize boring the participants. To decrease the variance across the sets, each set was required to have one rectangular maze, one curved wall maze, one large room with a generic texture, and one large room with a high orientation cue texture (e.g., bricks). Fortunately, when the effect of the rooms was tested with a nonparametric version of ANOVA, the set of rooms statistically displayed no effect.

A large screen display's glasses weigh less than an HMD, but as our HMD weight experiment demonstrated, headset weight is not a source of cybersickness. In the screen size experiment, a participant stood at different distances to achieve the same field of view. This changes the angular momentum and the accommodation of the eye.

The HMD blocked out most of the outside world while the large screen still allowed 100° of the real world to be seen despite a dimming of the room. This was in effect an independent visual background, the use of which has been shown to consistently decrease cybersickness.

Lastly, although the navigation paradigm encouraged the same type of interaction, there were differences between the HMD and large screen displays. When participants turned their head with the HMD, the application changed its view accordingly. When participants turned their head under the large screen condition, they were allowed to view more of the real world.

#### **4.5 Procedures and Measures**

All the experiments followed the same general procedure and employed the same virtual reality "treasure hunt" application. The participants signed a consent form before the experiments began, and all the participants were over the age of 18. The repeat sessions were

separated by a minimum of one week, and two weeks were encouraged to try to limit the habituation effect. The general set up was explained to the participants and then they put on the display, and a postural sensor was clipped to the back of their collars. They were then given an X-box controller for navigation. In the first session, the participants were given a tutorial so that they could learn how to work the controls and play the game. They were then placed into the full environment and instructed to locate menu items as quickly as possible.

The participants were instructed that they could stop at any time for any reason, and were monitored for symptoms every three minutes. They were asked, "On a scale of zero to ten, where zero is how you felt coming in, and ten is that you want to stop, where you are now?" The 0-10 scale is taken from *Bos et al.* who showed good correlation with the SSQ-T [94], but the question was rephrased to specifically avoid any references to illness or nausea to avoid demand characteristics [36]. This proved to be important as only a third of the participants that withdrew early specified nausea as the reason for stopping. The values used in this question are called "immersion ratings." The highest value of a participant's immersion rating during a session is called the "max immersion rating."

Immediately following the session, the participants were given the SSQ and one additional survey. In the initial session, the additional survey was the background survey. In the second session, the participants were given the MSSQ. The surveys were split to avoid survey fatigue. If participants attended both the weight and screen size experiments, a smaller background survey with just the display-specific question was administered after they used the large screen display for the first time. Many of the participants also gave informal feedback throughout the

virtual reality sessions and many of the early participants were asked if there was anything that could be done to improve the system. The SSQ was primarily used to compare the experiments.

## 5 Experiments

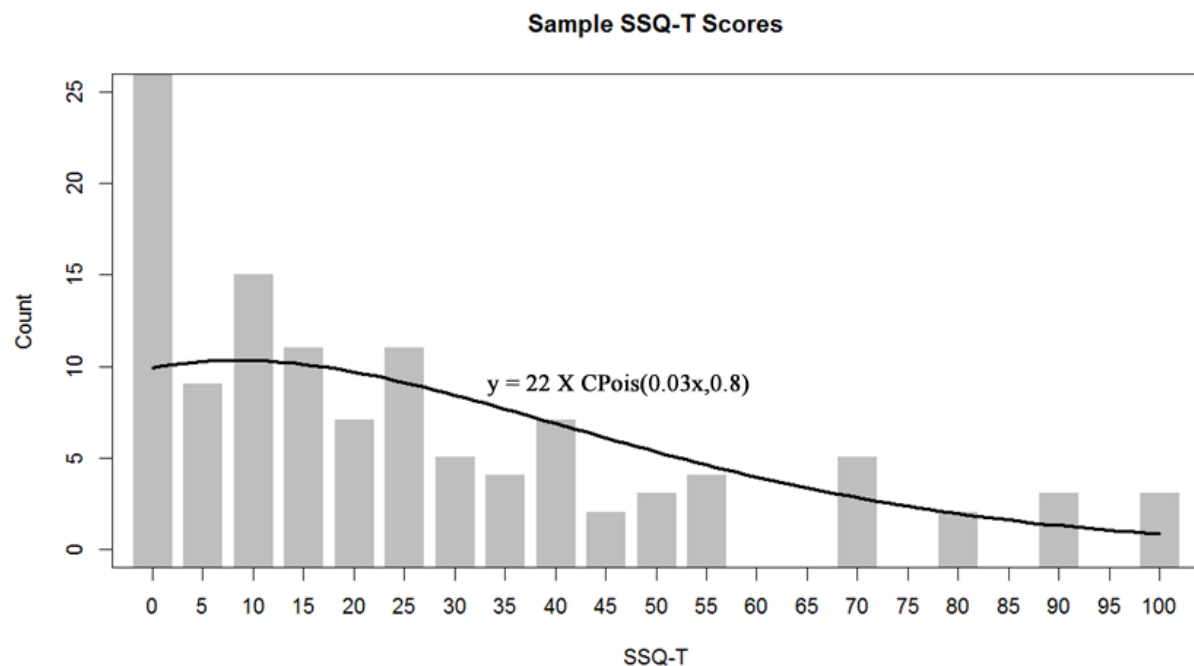
Three experimental sequences were performed as to further characterize the effects of several factors on cybersickness that had not previously been addressed in sufficient detail or with statistically significant results. These experiments addressed:

1. The effects of HMD weight.
2. Variations in screen size.
3. Impact of stereoscopic rendering.

The HMD weight experiment was performed first, followed by the screen size experiment. As these experiments were later used to compare the display types, the participants were asked to attend both the HMD and screen size experiment sets. However, due to incomplete experimental sets where participants did not complete both conditions, not all subjects participated in both the HMD weight and screen size experiment sets. The stereoscopic rendering experiment was performed last, while data for the individual factor analyses was collected during all experiments.

One issue with cybersickness data is the nature of the distribution. The SSQ is one of the standard measurements used in cybersickness research, but it is not a linear scale. A typical distribution is shown in Figure 17. Many standard statistical models assume the existence of a Normal, or Gaussian, distribution. When data is not normally distributed, it is typically transformed so that the normality condition can be met. Examples of these standard transformations include  $\frac{1}{x}$ ,  $\sqrt{x}$ , and,  $\log(x)$ . Cybersickness data is often skewed to the extent

that even with these transformations, the normality condition cannot be met. Accentuating this issue is the SSQ's oversensitivity, with SSQ-T values of 0 to 10 traditionally signifying no effect, or non-susceptibility. Non-susceptible participants encompass over 50% of the general population. Occasionally, existing studies have run analysis only using participant data with SSQ-T values greater than 10, but the percentage of non-susceptible participants is as important as the severity of symptoms in susceptible participants. As shown by *Rebenitsch and Owen [142]*, incorrect models can lead to unstable tests and faulty significant results. Therefore, paired non-parametric tests were used.

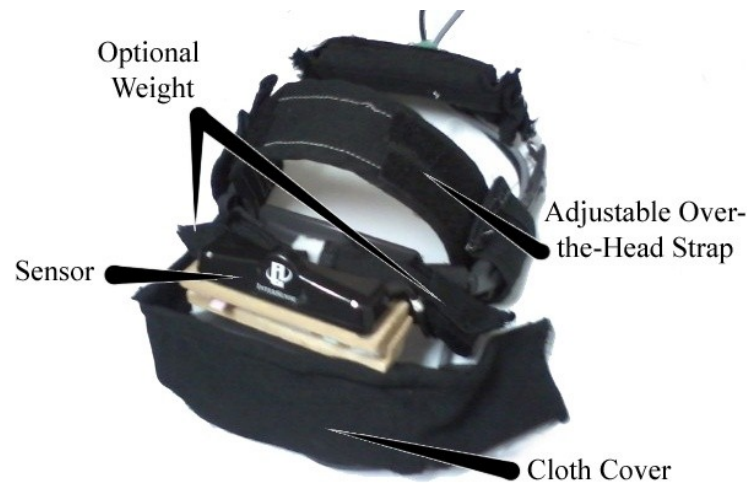


**Figure 17: Sample SSQ-T scores**

## 5.1 HMD Weight Procedures

The participants were recruited to test two different weight conditions. We used an HMD with a base weight of 340 grams. The weighted condition added 150 grams to the front of the display as seen in Figure 17. To relieve the pressure from the original narrow strap, the strap

was replaced with a padded version and an over-the-head band was added to further reduce the pressure on the participant's head. These changes made the display more similar to modern displays. We recruited 24 participants for both weight conditions. Their average age was 19.8 years with a standard deviation of 2.5 years. There were 5 females and 19 males. We had 4 early withdrawals, all males, out of 48 sessions.



**Figure 18: The Head Mounted Display**

The participants were requested to participate in the experiment twice, at least a week apart: once for the base condition and once for the weighted condition, in random order. The participants were also given one of two room sets in random order, although the Kruskal test (the Kruskal test is a non-parametric variant of ANOVA) analysis displayed no effect based on the choice of room set ( $p < 0.75$ ).

### **5.1.1 Specifications**

The application frame refresh rate was 60 Hz on average, but because it was rendered in stereo, the effective frame rate was 30 Hz per eye. The HMD was a Sony Glasstron LDI-D100B with an 800 X 600 resolution, a non-adjustable interpupillary distance, and a 35 degree diagonal



FOV. The application was rendered with a 33.3 degree diagonal FOV. The participants were permitted to take one step in each direction.

### **5.1.2 Results**

The SSQ-T scores were analyzed using a paired Wilcoxon test. This is a non-parametric test and has shown to be robust with respect to outliers in cybersickness data [142]. Paired tests were used since the same participant was in each condition, and paired tests are more sensitive to changes within a subject. The SSQ-T scores are used since they are the standard measure of total cybersickness, while the immersion scores were designed for monitoring participants. There was no effect of weight on cybersickness, with  $p < 0.88$ . The mean for the non-weighted condition was 23.12 with a standard deviation of 21.7, and the mean for the weighted condition was 29.6 with a standard deviation of 31.3, among those that completed sessions under both conditions. The mean and standard deviation are parameters for a normal distribute so they lose some of their meaning with non-Gaussian distribution of SSQ data.

The high  $p$  value means that the range of modern HMD weights is unlikely to affect cybersickness, and judging from the high  $p$ -value, even extremely lightweight HMDs are unlikely to have an effect. Therefore, the difference between HMD and other displays must lie elsewhere. This is of benefit to HMD developers because it means that additional hardware can be added without much cause for concern, except for one caveat. Although the HMD weight did not show an effect on cybersickness, the participants were vocal about the discomfort of the display. The heavier display placed more pressure on the bridge of the nose, and this additional pressure on the nose was nearly universally disliked. Therefore, while displays can be made heavier, they also need to disperse the weight away from the bridge of the nose. Heavier

displays may be less comfortable and, potentially, less competitive as a product, but they do not cause increased incidence of cybersickness.

## **5.2 Screen Size Procedures**

Participants from the HMD weight experiment were asked to attend the screen size experiment as well. A few participants attended only the screen size experiments. We recruited 22 participants for both screen experiments with an average age of 19.9 years and a standard deviation of 2.6 years. There were 5 females and 17 males. We had 2 early withdrawals out of 44 sessions, consisting of one male and one female participant.

In the screen size experiment, the participants were presented with a 113 centimeter screen or a 70 centimeter screen in random order. Two new room sets were created for the screen size experiment, which were presented to the participants in random order. Under both conditions, the participants were standing, had head tracking, experienced approximately the same ambient brightness, and were positioned so that they would have the same starting field of view. Since a temporary step in each direction was permitted, only the average field of view was identical for all the participants. Hardware limitations required the smaller screen to have 80% of the resolution of the larger screen. Angular momentum changes were associated with the displays, as the smaller displays had faster rotational velocities due to their larger relative changes in position. Similar to the HMD weight experiment, a Kruskal analysis of the room set order displayed no effect ( $p < 0.37$ ).

### **5.2.1 Specifications**

The application frame refresh rate was 100 Hz on average, but because it was rendered in stereo, it was effectively 50 Hz per eye. The refresh rate was a limitation of the active shutter

glasses. The projector was a stereoscopic capable InFocus DepthQ projector connected with a VGA cable. The maximum resolution was 1600 X 1200, and the image was displayed using a rear-projection screen. The screen sizes were 113 centimeters or 70 centimeters on the diagonal, and the participants were positioned so that they had a 35 degree average diagonal FOV. The 210 centimeter screen was rendered at an 800 X 600 resolution due the masking half of the display. Due to hardware limitations, the small screen was rendered at 80% resolution. Participants were permitted to take one step in each direction, but were required to return to their starting positions.

### **5.2.2 Results**

The SSQ-T was analyzed using a paired Wilcoxon test. Paired tests with the SSQ-T were used for the same reasons as the HMD experiment. There was no effect on cybersickness, with  $p < 0.66$ . The mean for the smaller screen was 18.5 with a standard deviation of 19.3, and the larger screen had a mean of 18.8 with a standard deviation of 15.7. As this is substantially different from a statistical trend, this means that the differences reported earlier between using monitors versus large screens are likely due to differences in the field of view, head tracking, or the use of standing versus seated participants. This also means that the distance to the screen likely has little effect. Given the low amount of physical movement in our study, the effect of angular momentum is still uncertain. Because the resolutions we used were so similar, resolution also remains an uncertain factor. This benefits cybersickness researchers because it means that the results from monitor experiments can be compared directly with the results from large screen experiments, assuming the remaining factors are held constant.

### **5.3 Display Type Procedures**

This analysis used the results from the HMD weight and screen size experiments. Both experiments used the same average field of view. The interaction between the two systems was also very similar. By adding the head tracked viewpoint directly on top of the controller position, the “forward” direction remained the same in both conditions. This encouraged the HMD participants to always face in the same direction as they would in a large screen environment. In addition, both the HMD and screen size conditions permitted only one step in any direction.

Since the HMD and screen size sessions showed no effects, a participant's scores within each of the two experiments were averaged. This has the added benefit of decreasing the effect of habituation on the data because the screen size experiments were performed after the weight experiments. Some habituation effect was expected, although there is no data showing that the habituation effect extends to other display types. If a participant chose not to attend both HMD sessions and both screen size experiments, their single score was left alone.

We had 24 participants with data for at least one HMD and one screen size experiment. These participants had an average age of 19.7 years with a standard deviation of 2.5 years. There were 5 females and 19 males. We had 7 early withdrawals out of 92 sessions, consisting of 6 males and 1 female. We had four participants miss either one HMD session or one screen experiment, either due to the participant's request or scheduling issues.

#### **5.3.1 Results**

The SSQ-T was analyzed using a paired Wilcoxon test as before. There was a significant effect on cybersickness, with  $p < 0.02$ . This suggests one or more of the following. There was an IVB

effect, the slight change in interaction had an effect, there was sufficient transfer of habituation, or a combination of these effects. The study by *Kershavarz, Hecht, and Zschuttschke* supports the IVB theory [82]. When they saw a difference between a large screen and HMD while holding the application, interaction, and field of view constant, they performed another experiment to clarify the effect. They masked the outside imagery in the screen condition so it would resemble that of an HMD, therefore eliminating the IVB effect. This change in configuration rendered the screen and HMD cybersickness results statistically equivalent. If the model found for IVB is used to convert the HMD scores to the projection screen IVB setting, there is no longer a statistical difference ( $p = 0.77$ ).

Our participants' HMD cybersickness scores were on average SSQ-T 9.7 higher than the large screen experiments. In *Kershavarz, Hecht, and Zschuttschke's* study, the SSQ-T average difference was 5.2 lower. This opposite effect may be due to different modes of interaction and applications. We used head tracking and participant controlled motion, while *Kershavarz, Hecht, and Zschuttschke* used a chin rest with no participant control with the visual stimulus of a moving car. There are two theories for these conflicting results. The effect of head tracking and user-controlled application interaction overshadows the effect of the display. Alternatively, the use of a chin rest made the large screen system seem more unnatural than the HMD system, which is expected to increase cybersickness according to rest frame theory.

Habituation might still be transferred to other displays, as later analyses of video games have shown. The overall effect of the minor difference in interaction is unknown and further studies are needed to clarify this effect.

## **5.4 Stereoscopic Rendering Procedures**

This experiment used the treasure hunt game application and used a large screen as before. Therefore, the same statistical tests were used as before. However, the participants were permitted to move freely, and the screen field of view was increased. A participant was presented with the application using stereoscopic or monoscopic viewing in random order, at least one week apart. Two new sets of rooms were created for the experiment, which were presented to the participants in random order. New participants were recruited for this study, although four participants from the earlier studies asked to attend, but only one participant completed both sessions. Fortunately, there was an average gap in time of one month between the screen and stereo experiments.

We had 28 participants, but 6 could not return due to time constraints, as this experiment was run near final exam time. The remaining participants were on average 21.4 years old with a standard deviation of 3 years. There were 8 females and 14 males. We had 8 early withdrawals out of 50 sessions, consisting of 5 males and 3 females. Two male participants withdrew twice.

### **5.4.1 Specifications**

The application frame refresh rate was 100 Hz on average, but because it was rendered in stereo it was effectively 50 Hz per eye. The refresh rate was a limitation of the hardware. The screen size was 225 centimeters on the diagonal, and participants stood wherever they pleased. The field of view was typically set between a 60-90 degree diagonal FOV. The screen was rendered at a resolution of 1600 X 1200. The participants were permitted to freely move in a 2 by 1.5 meter area.

### 5.4.2 Results

The SSQ-T was analyzed using a paired Wilcoxon test, and showed no cybersickness effect, with  $p = 0.22$ . There was still no effect after normalizing for the effect of habituation using the developed model ( $p = 0.19$ ). Several participants only showed a temporary effect and returned to their baselines within 10 minutes. The mean for the monoscopic condition was 28 with a standard deviation of 27.3, while the stereo mean was 33.3 with a standard deviation of 24.1 among those participants that completed experiments under both conditions. The results are tentative. Stereoscopic rendering may interact with the application. The human visual system only relies on stereo fusion out to several feet, and primarily within arm's reach. The visual system uses other visual cues to estimate the distance of farther objects. *Mon-Williams and Wann* also mentioned an effect on cybersickness if the focal distance changes frequently [98]. There also may be an underlying trait that makes someone susceptible or not to stereoscopic rendering. While more study is needed, one can conclude that the effect is likely to be small.

## 5.5 Individual Susceptibility Procedures

Immediately following a session, each participant was asked to fill out a usability survey after their first session and the MSSQ survey after their second session. These surveys are available in Appendix A. The survey questions included both usability and a broad range of background demographics. The reasons for the inclusion of the factors are available in Table XVII. An early analysis revealed that several of the factors under consideration were not viable or required further clarification. The usability survey was revised midway through the experiments. The original usability survey was administered to 20 participants from the HMD weight experiment set. There were 3 females and 17 males recruited for the study. The participants' ages ranged from 18 to 31 years, with all except one under the age of 22. Unfortunately, 4 participants

withdrew due to scheduling difficulties, and therefore these participants lack MSSQ data. The updated survey was given to 33 participants. One participant was removed from the analysis with the updated survey. This participant had very inconsistent results. On the MSSQ, he circled moderate susceptibility, but reported a MSSQ score of 0.

The MSSQ asks for the frequency of illness during several modes of travel in the last 10 years, and the history of motion sickness as a child under the age of 12. The scale used is 0, 1, 2, 3, 4, or “never”, “rarely”, “sometimes”, “frequently”, and “always”, respectively. Past research has suggested that specific modes of travel may be better correlated with cybersickness, specifically carnival ride sickness [23]. To ascertain a participant’s susceptibility to specific modes of travel values based on the MSSQ, the following function was used:

$$MSSQ_c = 2.64 * \frac{Child(m_c + v_c) + Adult(m_c + v_c)}{Child(t_c) + Adult(t_c)} \quad 6$$

In this equation,  $MSSQ_c$  is the MSSQ score of the subcategory,  $m_c$  is the motion sickness frequency of the subcategory,  $v_c$  is the vomiting frequency of the subcategory, and  $t_c$  is (1) if the participant has used that mode of travel, or (0) if the participant has never used that mode of travel.

The Kendall non-parametric test was used to test for correlations with the non-normalized data, and the Spearman test was used with ordered data (e.g., the frequency of 3D exposure).

### 5.5.1 Initial Results

Initially, we intended to include age and gender in the analysis. However, due to the unbalanced nature of the data, this analysis could not be performed. Age, in particular, is



difficult to model with an appropriate distribution, and studies typically require a primary focus on age or a publicly available system to gain an appropriate age distribution [55,56]. Only one participant had used an HMD before, so past display experience was eliminated from the analysis. Several categories naturally fell into bins. Game Play was binned into “rarely” (0-2 hours), “sometimes” (2.5-6 hours), and “regularly” (6.5 and over hours) per week. 3D Display Exposure was binned into “never”, “monthly”, and “yearly.” Hat usage was binned into “rarely” (less than 6 hours), “sometimes” (6-15 hours), and “frequently” (over 15 hours) per week.

We found significant correlations between SSQ and MSSQ ( $p < .03$ ), SSQ and MSSQ carnival ( $p < .01$ ), SSQ and max immersion rating ( $p < 0.001$ ), and SSQ and Vision correction ( $p < .01$ ). We found trends between SSQ and Game Play ( $p < 0.08$ ) and SSQ and MSSQ train ( $p < 0.055$ ). The adjusted coefficient of determination, or the adjusted variance, is provided for each individual factor in Table XIX. These values mean that Hats, past 3D Discomfort, VR Experience, and 3D Exposure can be eliminated from future consideration.

**Table XIX: Coefficient of Determination due to Characteristics**

|                                  | <i><b>Adjusted Coefficient of Determination</b></i> |
|----------------------------------|-----------------------------------------------------|
| <i><b>MSSQ</b></i>               | 10.8%                                               |
| <i><b>Video Games</b></i>        | 9.2%                                                |
| <i><b>Hats</b></i>               | -3.8%                                               |
| <i><b>Past 3D Discomfort</b></i> | -5.7%                                               |
| <i><b>VR Experience</b></i>      | -5.4%                                               |
| <i><b>Vision</b></i>             | 17.9%                                               |
| <i><b>3D Exposure</b></i>        | 0.3%                                                |

The adjusted variance, or the adjusted coefficient of determination, is better suited to small data sets. It considers the effect of each new item and only improves the variance if the effect is

better than random. This helps prevent over fitting, but the resulting values are always lower than normal variance and can become negative. If the adjusted variance becomes negative, the mean of the values is better correlated than the actual values.

While there was a correlation with vision correction and the SSQ, we had few participants that wore glasses exclusively, which made the results inconclusive. In addition, a subsequent analysis using multiple factors revealed a possible interaction between the MSSQ and Game Play. Greater detail on models using multiple factors is available in *Individual Variation in Susceptibility to Cybersickness (2014)* [54]. The following two linear models explained 43% and 58% of the adjusted variance, respectively. However, the second model's estimated terms failed to meet significance. Therefore, the first model has a better fit to the data.

$$\begin{aligned} \text{Suscept}_1(P) &= 0.76 p_{\text{Carnival}} + 3.14 \text{ (Weighted by Game Play)} & 7 \\ \text{Suscept}_2(P) &= 0.65 p_{\text{Carnival}} - 2.10 p_{\text{Contacts}} + 3.48 p_{\text{Glasses}} + 1.79 p_{\text{Both}} + 1.871 & 8 \end{aligned}$$

$\text{Suscept}_1$  and  $\text{Suscept}_2$  are estimates of susceptibility given a set of individual background demographics.  $P$  is the vector of background demographics for the participant,  $p_{\text{Carnival}}$  is the participant's carnival motion sickness score,  $p_{\text{Contacts}}$  is 1 if the participant wears contacts and a 0 otherwise,  $p_{\text{Glasses}}$  is 1 if the participant wears glasses and 0 otherwise, and  $p_{\text{Both}}$  is 1 if the participant wears both contacts and glasses and a 0 otherwise.

### 5.5.2 Additional Results

We examined the data for additional indications of correlation with the factors of video game genre, vision correction, and headaches. The MSSQ correlation followed the same trends as before. Correlations with the MSSQ modes of travel were also reanalyzed, and the additional modes of travel found to correlate to the SSQ-T are shown in Table XX.

The revised usability survey asked subjects to indicate not only their degree of game play, but also their game play in specific gaming genres such as first person shooters, platformers, etc. A wide variety of games was reported by the participants. Several *other* games were placed into different genres. These included moving "Grand Theft Auto" to *first person shooter*, MMOs to *RPGs*, and "Minecraft" to *platformer*. Sports, rhythm, and strategy games remained in the *other* genre. The Spearman correlation was selected for video game play over the Kendal correlation because the Spearman reacts stronger to the degree of distribution. Therefore, the Spearman correlation is more appropriate when the degree of difference is important, such as with game play. This is less true with the MSSQ and SSQ, which are non-linear.

Separating video game play into separate genres helped clarify the effects, as seen in Table XXI. Overall game play no longer had a correlation to cybersickness, but specific genres did. First person shooters and platformers have the strongest correlations with cybersickness. Both of these genres have large amounts of forward motion and are the most similar to many virtual environments. Game play does not correlate with the MSSQ, as seen in Table XXII.

The effect of vision was no longer statistically significant after including participants from the screen size and rendering experiments. The average SSQ-T was found for each category per experiment set, as seen in Table XXIII. The numbers of participants in each category were very unevenly distributed (e.g., there were only two participants that wore contacts for the rendering experiment). The standard deviation for all the values was quite high, with most conditions having a standard deviation greater than 20. No grouping was found to reach

statistical significance, with the lowest p values equal to 0.19 which occurred when people who wore both glasses and contacts were compared to all the other participants.

Therefore, we conclude that vision correction is either unlikely to have more than a small effect, or only has an effect with HMDs. The uneven distribution may mask the effect, but the high standard deviation signifies that any effect would be minor. The revised survey was given primarily to the projection screen participants and glasses were more likely to be an issue with the HMDs. There were not a sufficient number of participants in each condition to test for any differences between them.

Headaches correlated to the SSQ but did not correlate to the MSSQ or the primary genres of game play as shown in Table XXIV.

**Table XX: MSSQ Correlations**

|                    | <i>Self-Limiting<br/>Immersion Rating and<br/>MSSQ</i> | <i>MSSQ and<br/>SSQ</i>            | <i>MSSQ<br/>Airplane and<br/>SSQ</i> | <i>MSSQ Train<br/>and SSQ</i>        | <i>MSSQ<br/>Playground<br/>and SSQ</i> |
|--------------------|--------------------------------------------------------|------------------------------------|--------------------------------------|--------------------------------------|----------------------------------------|
| <b>Correlation</b> | -0.07                                                  | 0.25                               | 0.16                                 | 0.2                                  | 0.16                                   |
| <b>P -value</b>    | 0.51                                                   | 0**                                | 0.02*                                | 0.003*                               | 0.016*                                 |
| <b>Test</b>        | Pearson                                                | Kendall                            | Kendall                              | Kendall                              | Kendall                                |
|                    |                                                        |                                    |                                      |                                      |                                        |
|                    | <i>MSSQ Playground and<br/>SSQ</i>                     | <i>MSSQ Small<br/>Boat and SSQ</i> | <i>MSSQ<br/>Carnival and<br/>SSQ</i> | <i>MSSQ Big<br/>Boat and<br/>SSQ</i> | <i>MSSQ Cars<br/>and SSQ</i>           |
| <b>Correlation</b> | 0.16                                                   | -0.02                              | 0.17                                 | 0.07                                 | 0.17                                   |
| <b>P -value</b>    | 0.016*                                                 | 0.82                               | 0.008**                              | 0.27                                 | 0.009**                                |
| <b>Test</b>        | Kendall                                                | Kendall                            | Kendall                              | Kendall                              | Kendall                                |

Table XXI: Binned Game Play and SSQ Correlations

| <i>Binned</i>      | <i>Game Play and SSQ</i> | <i>Game Play shooter and SSQ</i> | <i>Game Play platformer and SSQ</i> | <i>Game Play driving and SSQ</i> | <i>Game Play RPG and SSQ</i> | <i>Game Play fighting and SSQ</i> |
|--------------------|--------------------------|----------------------------------|-------------------------------------|----------------------------------|------------------------------|-----------------------------------|
| <b>Correlation</b> | -0.11                    | -0.34                            | -0.29                               | 0.09                             | 0.28                         | 0.23                              |
| <b>P -value</b>    | 0.19                     | 0.002                            | 0.011                               | 0.46                             | 0.02                         | 0.05                              |
| <b>Test</b>        | Spearman                 | Spearman                         | Spearman                            | Spearman                         | Spearman                     | Spearman                          |

Table XXII: Binned Game Play and MSSQ Correlations

| <i>Binned</i>      | <i>Game Play and MSSQ</i> | <i>Game Play forward and MSSQ</i> | <i>Game Play shooter and MSSQ</i> | <i>Game Play platformer and MSSQ</i> | <i>Game Play driving and MSSQ</i> | <i>Game Play RPG and MSSQ</i> | <i>Game Play fighting and MSSQ</i> |
|--------------------|---------------------------|-----------------------------------|-----------------------------------|--------------------------------------|-----------------------------------|-------------------------------|------------------------------------|
| <b>Correlation</b> | -0.08                     | -0.09                             | -0.19                             | 0.09                                 | 0.29                              | -0.001                        | 0.13                               |
| <b>P -value</b>    | 0.55                      | 0.62                              | 0.31                              | 0.64                                 | 0.12                              | 0.99                          | 0.5                                |
| <b>Test</b>        | Spearman                  | Spearman                          | Spearman                          | Spearman                             | Spearman                          | Spearman                      | Spearman                           |

Table XXIII: SSQ-T Values for Vision

|                      | <i>None</i> | <i>Contact</i> | <i>Glasses</i> | <i>Both</i> |
|----------------------|-------------|----------------|----------------|-------------|
| <b>HMD</b>           | 31.56       | 27.42          | 24.93          | 12.45       |
| <b>Screen</b>        | 24.5        | 16.8           | 19.4           | 16.2        |
| <b>Render</b>        | 30.3        | 62.6           | 30.4           | 29.9        |
| <b>Total Average</b> | 28.6        | 28.6           | 27.6           | 19.5        |

Table XXIV: Headache Correlations

|                    | <i>Max Immersion Rating and SSQ</i> | <i>Headaches And SSQ</i> | <i>Migraines And SSQ</i> | <i>Headaches And MSSQ</i> | <i>Migraines And MSSQ</i> | <i>Headaches and Binned platformer</i> | <i>Headaches And Binned Shooters</i> |
|--------------------|-------------------------------------|--------------------------|--------------------------|---------------------------|---------------------------|----------------------------------------|--------------------------------------|
| <b>Correlation</b> | 0.5                                 | 0.266                    | 0.021                    | 0.244                     | -0.20                     | 0.05                                   | 0.2                                  |
| <b>P -value</b>    | 0**                                 | 0.02*                    | 0.86                     | 0.21                      | 0.31                      | 0.78                                   | 0.255                                |
| <b>Test</b>        | Kendall                             | Spearman                 | Spearman                 | Spearman                  | Spearman                  | Spearman                               | Spearman                             |

We can conclude that there are three individual susceptibility factors correlated with cybersickness, which are independent of each other. For an individual susceptibility model, the effects of the experiments would need to be normalized. To convert from the screen size experiment to the HMD experiment, the values are multiplied by 1.431 to remove the IVB effect. To convert from the rendering experiment, the values are multiplied by 1.431 to remove the IVB effect and by 0.53 to counteract the increase in screen size. The best linear model of the MSSQ to the SSQ, which explains 30.5% of the adjusted variance, is where  $p_{mssq}$  represents the participant's MSSQ score in the following equation:

$$M\_Hist(P) = 14.53 + 0.484 * p_{mssq} \quad 9$$

The best model for game play used binned shooters and platformers. Fighting games were dropped due to a poorer model. In the  $P$  demographic vector, a participant had a 1 in their assigned video game bins, and a 0 in all the other bins. For example, if a participant played shooters rarely and platformers regularly, their video game subset would be  $\langle 1, 0, 0, 0, 1, 0 \rangle$ , where the values represent rare shooter (shootRare), regular shooter (shootReg), frequent shooter (shootFreq), rare platformer (platRare), regular platformer (platReg), and frequent platformer (platFreq), respectively. The following equation explains 6% of the adjusted variance in the data:

$$Video(P) = 51.702 - 4.25p_{shootRare} - 22.949p_{shootReg} - 17.57p_{platRare} - 20.607p_{platReg} \quad 10$$

The best model found for headaches explained 15.8% of the adjusted variance where  $p_{Headache}$  represents the number of headaches per month:

$$Head(P) = 21.7 + 5.55p_{Headache} \quad 11$$

Simply using the MSSQ, headache, and video game play functions, 37.2% of the adjusted variance in the data was explained. This function can be written as:

$$Ind(P) = -2.12 + 0.566 Video(P) + 2.61p_{headache} + 0.38p_{MSSQ} \quad 12$$

The low variance is not surprising as it only considers the individual portion of the results and not the variation due to different configurations and other external factors. There are two further limitations to this model. As expected, the values within the model do not follow a Gaussian distribution, which decreases the accuracy of linear models. The video game term only had a trend of  $p = 0.8$  and the headache term did not reach significance ( $p = 0.11$ ) in the model, which indicates a weaker fit to the data. This is not surprising, given the relatively lower variance that can be explained by their factors.

## 5.6 Participant Preferences

The participants gave both informal and formal feedback on their preferences. This feedback can be used to identify potential factors, to build better systems, and to predict how participants will use virtual reality.

The self-limiting immersion rating originally showed a significant correlation with the MSSQ, but increasing the number of participants in the analysis made this no longer true, with  $p=0.6$ . The last question in the survey was open-ended, and asked about other potential uses of virtual

systems. The uses suggested by the participants varied according to the display used. The participants' write-ins for *other* included:

1. Would be cool to use virtual reality for school
2. Google street view
3. Training and target practice
4. Virtual tour of Campus. Cities. Possibly concerts.
5. Campus tours or building tours
6. For some sort of interactive data visualization type thing it could be really useful
7. Virtual reality travel (vacation)

The participants also stated that they would like to see virtual reality in wider use, but only in certain contexts. The percentage of participants that would use each device is shown in Table XXV to Table XXVII.

**Table XXV: HMD Preferences**

|                 | <i>Watching TV</i> | <i>Movies</i> | <i>Video games</i>     | <i>Landmark exploration</i> |
|-----------------|--------------------|---------------|------------------------|-----------------------------|
| <b>TV</b>       | 90%                | 90%           | 25%                    | 20%                         |
| <b>VR</b>       | 10%                | 10%           | 70%                    | 70%                         |
| <b>Write In</b> | 0%                 | 0%            | 1) Depends on the game | 1) Real life<br>2) Depends  |



**Table XXVI: Large Preferences**

|                 | <i>Watching TV</i>     | <i>Movies</i> | <i>Video games</i>     | <i>Landmark exploration</i> |
|-----------------|------------------------|---------------|------------------------|-----------------------------|
| <b>TV</b>       | 44                     | 40            | 13                     | 5                           |
| <b>VR</b>       | 2                      | 7             | 33                     | 41                          |
| <b>Write In</b> | 1) Depends on the show |               | 1) Depends on the game | 1) Both                     |

**Table XXVII: Cumulative Preferences**

|                 | <i>Watching TV</i> | <i>Movies</i> | <i>Video games</i> | <i>Landmark exploration</i> |
|-----------------|--------------------|---------------|--------------------|-----------------------------|
| <b>TV</b>       | 73                 | 67            | 22                 | 9                           |
| <b>VR</b>       | 4                  | 11            | 54                 | 65                          |
| <b>Write In</b> | 1                  | 0             | 2                  | 3                           |

### 5.6.1 Informal Feedback

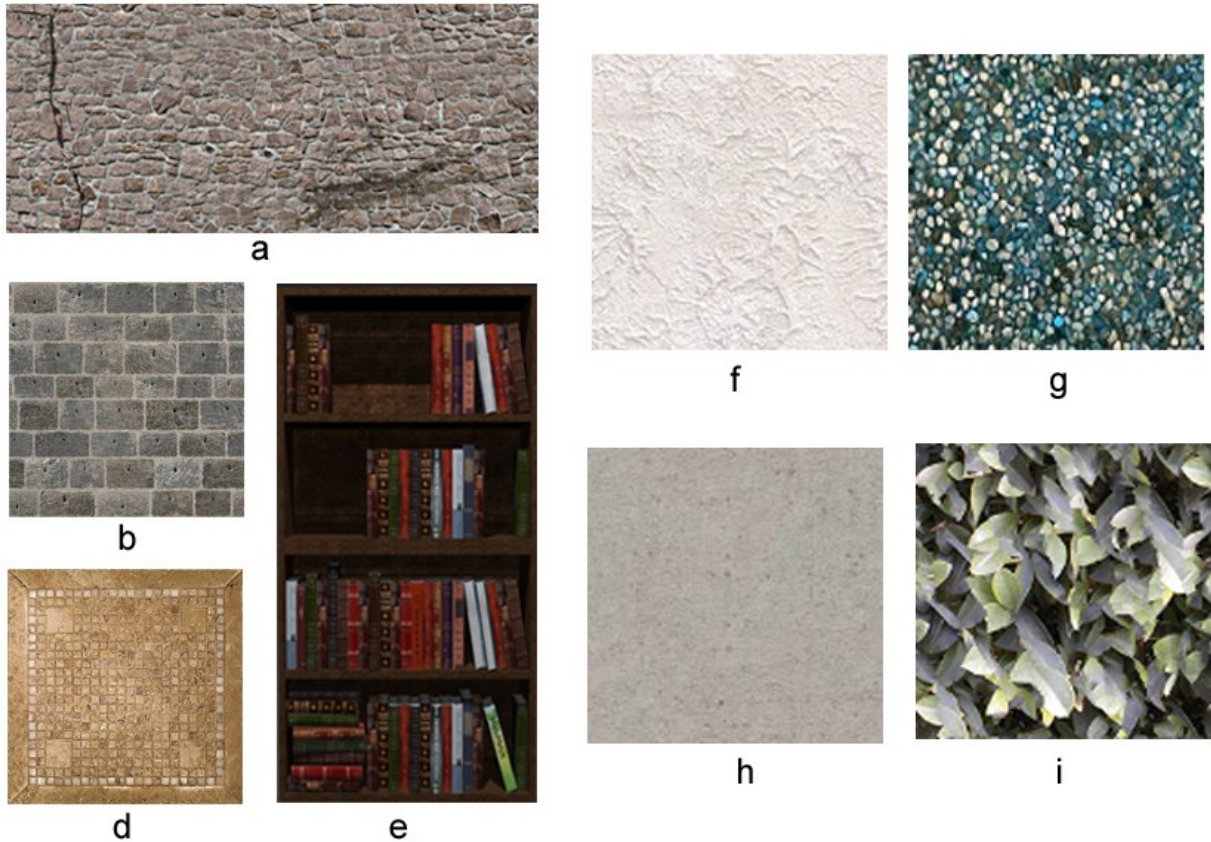
The participants made comments during their use of the virtual reality system, and we observed certain commonalities. A discussion of information feedback and world design recommendations are provided in much more detail in *World and Object Designs for Virtual Environments (2014)*[143]. Minor difficulties relating to game play were fixed during the experiments. These difficulties included minor texturing problems, object orientation, and menu readability. Early participants commented that the menu text was difficult to read at times. Therefore, the text size was slowly increased. Correcting for object orientation was more difficult. Flat objects (e.g., plates), small objects (e.g., pencils), and low objects (below 80 cm) were difficult for participants to identify. Flat and low objects were easily fixed by rotating an object upwards and raising the shelves several centimeters, respectively. The small object issue could not be resolved because the objects were kept to-scale if possible. The smallest readily identifiable size appeared to be an 8 centimeter cube, and it was only identifiable if there was

good color variation. Participants made several “feature requests”. Though not added, these included sounds, true jumping, blowing up walls, animation, adjustable controls, monsters, and more action in general.

Navigation through the virtual environment proved to be difficult for many of the participants. Restricting the field of view made participants forget where they had been and made them more likely to miss nearby objects. Direction markers were added to the maze room to help with navigation and were specifically referenced the first time the participant entered a maze. These markers only slightly improved navigation. In the stereoscopic viewing experiment, which effectively doubled the field of view, navigation was much less of an issue. Many of the participants frequently ran into walls. In the earliest rooms, the hallways were rendered to-scale and were 1.85 meters wide, but these hallways proved to be much too narrow. The hallway sizes were slowly increased in each new room model. The smallest acceptable hallway size was 3 meters for a small field of view and 2.75 meters for a large field of view. Another unexpected participant behavior was that certain corridors were ignored during navigation. In two rooms, there was a hallway with four corridors branching off one side. For unknown reasons, many of the participants frequently skipped the second corridor.

Although we were not testing the virtual environment visuals directly, there were some consistent comments about problematic areas. Generic, low orientation textures, as shown in Figure 19 *f-g* were problematic, with *g* being nearly universally disliked. The high orientation textures in *a-e*, particularly those with non-repeating patterns such as “*a*” and “*e*,” were less likely to cause issues. As mentioned earlier in the literature review, faster navigation is

associated with increased cybersickness. Judging from their comments, the participants seemed to be in agreement that the run button should be used sparingly, with one participant commenting "the run button is the sickness button."



**Figure 19: Sample Textures**

## **5.7 Cumulative Analysis and Results**

A set of models was derived from the literature review and our experiments. Because cybersickness values are relative, direct modeling is not viable. Thus, these values must be estimated from the percent change of SSQ-T value based on prior studies. The results in the following models estimate the percentage that  $B$ 's SSQ-T changes from  $A$ , where  $A$  is a prior

study's configuration factor vector and  $B$  is a new configuration with a change in only one factor:

$$Duration(A, B) = \frac{Time(B)}{Time(A)} \quad 13$$

$$FOV(A, B) = \begin{bmatrix} a_{FOV} > b_{FOV} & FOV(A, B) \\ a_{FOV} < b_{FOV} & \frac{1}{FOV(A, B)} \\ a_{FOV} = b_{FOV} & 1 \end{bmatrix} \quad 14$$

$$IVB(A, B) = \begin{bmatrix} a_{IVB} = b_{IVB} & 1 \\ a_{IVB} = false \text{ and } b_{IVB} = true & 0.699 \\ a_{IVB} = true \text{ and } b_{IVB} = false & 1.431 \end{bmatrix} \quad 15$$

$$Habituation(A, B) = \begin{bmatrix} a_{order} \leq b_{order} & 0.882^{b_{order}-a_{order}} \\ a_{order} > b_{order} & 1.134^{a_{order}-b_{order}} \end{bmatrix} \quad 16$$

$$Individual(A, B) = \frac{Ind(B)}{Ind(A)} \quad 17$$

$$Video(A, B) = \frac{Video(B)}{Video(A)} \quad 18$$

$$Headaches(A, B) = \frac{Head(B)}{Head(A)} \quad 19$$

$$Speed(A, B) = \frac{Speed(B)}{Speed(A)} \quad 20$$

There are diminishing returns on habituation over time and the model would be more accurate if it included the smaller decreases associated with longer time periods, but there have been few studies that have spaced their sessions over one week apart.

Using these results, two models were tested for their predictive capability. Direct linear modeling was used for its simplicity and ease of use. Linear modeling permits direct use of the data from the literature, but potentially suffers from the highly skewed and individualized nature of cybersickness. The second model tested was a zero-inflated negative binomial distribution model (ZINB). This model readily permits the modeling of individual effects and takes into account the large percentage of people who do not become ill. The ZINB model is not

widely supported, and when it is supported, it has restrictions on the format of the data, which will be discussed in greater detail in Section 5.9.

## **5.8 Linear Model using Reported Configurations**

Linear models using individual data have been attempted before. *Kolasinski* also had a linear model which explained 34% of the variance of the data [1]. As the author mentioned, the highly skewed data of cybersickness makes a linear model unreliable. In our model, the results of previous studies are used rather than the individual results, which should slightly lessen the detriment on its reliability. This approach does, however, have the unwanted effect of making any predications general to the population and unusable for dynamic adjustments to individuals. However, it does provide a method to estimate the effect of a new virtual reality system before time and capital are invested in creating the system.

The experimental configurations and their resulting SSQ-T values were recorded from the literature and are available in Appendix B. Only those studies that reported an SSQ-T value or a means to convert to an SSQ-T value, as well as a sufficient number of hardware and software factors, were included. Because study conditions are normally random or use different individuals, habituation was dropped from the analysis. For the analysis, if stereoscopic rendering was not specified, monoscopic rendering was assumed. While some of the factors did not have enough support to create a model, they were reported frequently enough to be included in the analysis. These factors include realism, seated, head tracking, and the controller. The levels of the controller were limited to joystick (gamepad), simulator, mouse, head, and none. Although we found no cybersickness effect with stereoscopic rendering, others have found such an effect, so it was kept for analysis. Factors such as head tracking are likely

affected by the number of orientations that are supported and interaction with the controller, but these effects are currently unknown. Therefore, head tracking was represented as “yes or no” if head tracking was provided and head movement was permitted.

Many variables were undefined in their respective publications. If realism was not given, age and implied content were used to estimate its value. Displays were converted into those that were likely to have an IVB effect or not. However, there are many ways to achieve an IVB effect. Simply increasing tactile feedback, as was done in *Hakkinen, Vuori, Puhakka* [61], can achieve an IVB effect. The chair used in their movie condition had more postural support, yielding an IVB like effect. *Jaeger and Mourant’s* treadmill was considered to be a simulator for the purpose of the analysis. The missing head tracking and sitting values were replaced by the implied method in their publications. *Sharples et al.* did not report the field of view in several of their conditions [108]. The projection screen was assumed to have a smaller field of view than the reality theater system and the monitor was assumed to be viewed at a comfortable distance. The converted values are available in Appendix B. To test for direction, the *y/n* factors were converted to *1/-1*, respectively. The realism factor range was converted to 0, 1, 2, and 3 (low, medium, high, and realistic, respectively). The percent changes were used directly in the model, rather than having the original SSQ-T values first adjusted by the earlier created equations.

A linear model using all the factors with a 2 way interaction explained 70.2% of the adjusted variance. While this is a great improvement over the 34% reported earlier, our model is too complicated to be of practical use. It includes 396 terms, and the vast majority of these terms

did not reach significance. This means that the model was over fitted, and the majority of the coefficients did not reach statistical significance. The best model with exclusively significant terms is Equation 23, below. All terms except the initial SSQ-T ( $a_{ssq}$ ), which had a  $p = 0.03$ , had a statistical value of  $p < 0.0001$ , which represents a good fit. The  $Predict(A,B)$  model explained 54.5% of the adjusted variance where  $x_{tracking}$  is 1 if the participant was head-tracked and 0 otherwise,  $x_{realism}$  is the 0-4 value for realism,  $x_{control}$  is the controller used,  $x_{sitting}$  is 1 if the participant was seated and 0 otherwise for configuration X.

$$Controller(A) = \begin{bmatrix} a_{control} = None & -9.56 \\ a_{control} = Mouse & -15.44 \\ a_{control} = Joystick & 33.65 \\ a_{control} = Simulator & -8.55 \end{bmatrix} \quad 21$$

$$Movement(A) = \begin{bmatrix} a_{control} = None & 11.88a_{tracking} \\ a_{control} = Mouse & 20.78a_{tracking} \\ a_{control} = Joystick & -22.56a_{tracking} \\ other & 0 \end{bmatrix} \quad 22$$

$$\begin{aligned} PredictB(A,B) &= 33.61 - 0.2a_{ssq} - 4.04b_{realism} - 10.21FOV(A,B) \\ &+ 2.48Duration(A,B) - 7.65b_{tracking} + Controller(B) + 5.61b_{sitting} \\ &+ 0.27a_{ssq}FOV(A,B) - 4.60b_{realism}b_{ivb} + 6.88b_{realism}b_{fov} \\ &+ Movement(B) \end{aligned} \quad 23$$

Improved models can be expected if multiple nearby points are used to estimate the effect. Some of the interactions are unsurprising. An IVB deals with the enforcement of participants' expectations, so the realism of the scene could affect the amount of presence, or the participant's belief of "being there." Head tracking and the controller are directly related, and the presence or absence of head tracking will greatly affect how the controller works. What is surprising is the small effect of  $a_{ssq}$ , or the SSQ-T value from configuration A that is used as a

starting point. Stereoscopic rendering by the FOV could be added to the model to explain another 0.4% of the adjusted variance, but such a model has a slightly poorer fit to the data.

Some of the issues with the model are that it does not account for the individual, and the individual alone can explain 30-40% of the variance. Because the results that were used for the analysis are summary statistics, this effect is expected to be reduced, but another 10-20% of the variance is still likely due to individual differences in the study populations.

## **5.9 Zero Inflated Model using Experimental Results**

*Rebenitsch and Owen* found that zero-inflated negative binomial models showed promise as future predictive models [142]. The zero-inflated negative binomial (ZINB) model includes a probability parameter for a zero-class (well group). If a data point falls into the non-zero class (ill group), the distribution follows a negative binomial distribution. A negative binomial distribution is essentially an over-dispersed Poisson distribution. However, it is not well supported in statistical packages and requires an adjustment of the data if it is to be used. The negative binomial portion of the model requires integer count values. Therefore, all the SSQ-T data must be rounded to the nearest integer, making the results more similar to a count of symptoms multiplied by their severity. Since our reported SSQ ranged from 0-150, this minor decrease in accuracy is acceptable. The original ZINB model also requires that the well-group have the same zero value. Therefore, all the values below a certain threshold must be set to 0, and the remaining values must be decreased by that threshold to maintain continuity. From the literature review, the standard SSQ-T interpretation of a rating that is less than 10 as "well" does not seem to be true. Many of the well participants reported values of up to 15. Therefore the cut off for the well group was changed to 15.



We dropped two participants from the analysis. One participant "could not remember" if he became sick and the other participant had the extremely inconstant MSSQ as mentioned earlier. The original usability survey did not include the game genre or headache factors, but removing the original study values would eliminate most of the HMD participants from consideration. Setting a value of zero for all the participants would likely mask the results, so their answers were estimated. For game play, the average number of hours was known, and most participants tended to favor one genre. For example, someone who played 10 hours of video games would have 7 hours of playing "shooters" and 3 hours of playing another category. Therefore, we could estimate their genre game play by the frequency of the genre and their hours of game play.

Estimations of the headache and MSSQ responses were less accurate. The headache response had to be estimated using random sampling, and weighted directly from the correlation estimate from their SSQ-T scores and the frequency of each answer. This has the unfortunate potential effect of forcing the data to fit the model for these participants. The MSSQ had to be estimated directly with random distribution from its standard deviation. Fortunately, there were only a few participants that did not fill out an MSSQ.

The total number of sessions was 147. Of these, 140 sessions had an associated MSSQ, 75 had completed revised usability surveys, and 71 that generated complete data sets.

Because the ZINB model does not use standard linear models, calculating its variance is highly questionable. Therefore, the goodness of fit models is estimated from the residuals from a fitted model, with a lower average absolute residual representing a better model. To reflect the

fact that stereoscopic viewing and IVB can affect the direction of the results in both directions, these values were transformed to “-1” for “no” and “1” for “yes.”

When creating the ZINB model, both the raw data and the data that were converted using single factor models were tested. Using all the factors and the raw data, the ZINB regression created a model with an average residual of 0.69 and a standard deviation of 0.88. The best model found had statistical significance  $p < 0.05$  for all its terms, an average absolute residual mean of 0.66 and a standard deviation of 0.85. Two terms were found for the negative binomial portion of the model: *Habit(A)* by field of view and IVB by Headache by *Video(A)*. The zero/well class prediction terms were: the MSSQ, binned first person shooters, headaches, *Habit(A)*, and Stereo. The *Stereo* term in the negative binomial portion could be dropped with little effect on the residuals, but this caused the term to lose its statistical significance. The coefficient values are shown in Table XXVIII.

**Table XXVIII: ZINB Model Terms**

| <b>Negative Binomial</b>                 |                    |                                    |                                                       |                    |                |
|------------------------------------------|--------------------|------------------------------------|-------------------------------------------------------|--------------------|----------------|
|                                          | <i>Intercept**</i> | <i>Habit(A)</i> by<br><i>FOV**</i> | <i>IVB</i> by headache by <i>Video</i><br><i>(A)*</i> | <i>Log(Theta)*</i> |                |
|                                          | 2.69               | 0.001                              | -0.002                                                | 1.59               |                |
| <b>Zero-Inflation Model Coefficients</b> |                    |                                    |                                                       |                    |                |
| <i>Intercept**</i>                       | <i>MSSQ**</i>      | <i>Video(A)*</i>                   | <i>Headache(A)*</i>                                   | <i>Habit(A)*</i>   | <i>Stereo*</i> |
| 7.95                                     | -0.03              | -0.06                              | -0.04                                                 | -4.74              | -0.75          |

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This model implies a few traits about the nature of the data. Stereo is still a small term, but it greatly affects other factors, which explains the conflicting results on this factor in the literature. Most of the terms are part of the “well” class predictor or concern items that are

individualistic. This means if the individual is factored out, there is a moderate, rather than large, effect imparted by the equipment. If the “well” grouping terms are placed in a linear model, they explain 23% of the adjusted variance of the system.

This model provides a better means to determine what will happen to a particular person in a particular virtual environment. The prior models either predict how sensitive a participant is to cybersickness, or predict what would occur to a general population with a particular configuration. Models using hardware, software, and individual terms could be utilized to give better guidance to a person. The ZINB model is also more sensitive to susceptibility effects on statistical results. If a resistant individual becomes ill, it has a stronger meaning than if a highly susceptible person will be ill.

## 6 Conclusion and Future Directions

Cybersickness remains a complex issue to describe and study. Individual models yield an explanation of adjusted variance of 37%, while cross configuration models developed from the literature explained an adjusted variance of 55%. If these results were purely additive, 92% percent of the variance in a system could be explained by these variables. It is more likely that the explained variance is approximately 75-80%. Determining the actual variance is not possible without including individual participant data from other experiments. This is a large improvement over *Kolasinski's* model that explained 34% of the variance [9]. The models suggested by *So* [10], *Simon* [13], *Jones, Kennedy, and Stanney* [14] do not account for the individual. *Simon* and *Jones, Kennedy, and Stanney* both require a large number of configurations to be tested in a uniform fashion using the same measures. The cybersickness literature does not meet these requirements. The zero-inflated negative binomial (ZINB) model, as developed, mixes raw data and modeled results. The ZINB model also follows the distribution of the data more closely. Using both individual and configuration data results in higher accuracy, with residuals that are less than one on average.

A literature review of the factors proposed by *Kolasinski* [9] and *Renkewitz and Alexander* [48] revealed only a few factors with sufficient evidence that would be suitable for use in potential virtual system guidelines. These include the real field of view, independent visual background, habituation, and duration. Several factors have shown consistent and strong results, but others would greatly benefit from additional data points, including the navigation speed and sitting versus standing factors.

Several other factors displayed a potential to greatly affect cybersickness, but these factors have limited data. These factors include scene realism, initial postural stability, change in postural stability, the ratio between the virtual and real field of view, method of movement, and head tracking. Originally, the type of display showed promise as a cybersickness factor, but the recent results of IVB studies and our own results suggest that the differences associated with them are due to other factors.

One major difficulty in studying the effects of cybersickness is the variability in individual susceptibility. Within subject experiments are more likely to detect effects, but using the same participants over multiple sessions suffers from the effects of habituation. There are also questions of how the results will generalize to a normal population as participants tend to be self-selecting. Ideally, the individual aspect should be normalized before any comparisons are made, but studies on individual susceptibility to cybersickness are limited. Moreover, results from motion sickness studies may not necessarily apply to cybersickness studies [55]. Therefore, far more research on individual susceptibility to cybersickness is needed. However, several of the individual factors that have been suggested are time consuming or difficult to assess. These include interpupillary distance (IPD), mental rotation, perceptual style, and body mass index (BMI). One individual characteristic that is in critical need of study is whether habituation with different configurations transfers to new virtual reality systems.

Several models were developed during our experimentation for different purposes. These are single factor models that can be used for virtual system guidelines and normalizing results. Individual susceptibility prediction models can be used to dynamically adjust a virtual reality

application to a participant. The *Individual(A, B)* from Equation 17 may be used to normalize a population to allow different groups of individuals to be tested. To normalize, a standard target value is necessary. The motion sickness susceptibility questionnaire (MSSQ) average is approximately 40, and may be the best choice for generalization. Cross configuration prediction models are useful in that they can estimate the effects of a new virtual reality application before any time or capital is spent developing it. The cross configuration models also permit the comparison of results from different publications.

Based the single factor models, the following guidelines are proposed:

1. If a participant is highly susceptible, shrink the field of view with its effect modeled by Equation 3.
2. Use an independent visual background (IVB) whenever possible. The expected change in effect is modeled by Equation 5
3. Keep forward movement slow. If there is some user interface akin to a run button that allows a participant to move more quickly than would be natural, limit the amount of time the run button can be used. The expected change in effect is modeled by Equation 4.
4. Participants generally develop tolerance to cybersickness-inducing stimuli if they are subjected to repeat sessions. Habituation also can develop through playing video games with a large amount of forward movement such as that found in first person shooters and 3D platformer games. If a system needs to be used over a longer time period,

shorter repeat sessions can build tolerance. The expected change in effect is modeled by Equation 1.

5. Longer sessions are more likely to cause illness. The expected change in effect is modeled by Equation 2.
6. Have different configuration schemes for low, moderate, and highly susceptible participants. Administer a short susceptibility test prior to the participant's first use of a system to incorporate suggestions. The model provides 12 questions as an estimate, but Golding has proposed a much shorter susceptibility test that is likely to be better suited to cybersickness studies [144]. Since the tolerated symptoms differ between individuals, permit the scheme to be set by the user.

Our statistical results have implied the following suggestions for researchers and developers:

1. Estimate a new configuration and application effect. Use the model Equation 23 before building a system.
2. If the population and configuration are known, Equation 24 can provide an estimate of the effect.
3. The effects of habituation can be normalized, and within subject design is better at detecting effects.
4. Cybersickness data is not normally distributed. Nonparametric statistical tests are required.

5. For ease of comparison with other publications, the field of view, the display/IVB, the controller, duration, sitting or standing conditions, history of motion sickness, amount of motion, and scene complexity should be reported.

Design suggestions are available in *Rebenitsch, Owen, and Coburn* [143]. The individual susceptibility model in Equation 12 could be used to allow commercial virtual reality applications to make suggestions on the rendering appearance for an individual. For example, if this formula yields a low 5, the participant is unlikely to become ill, so high speeds, wide fields of view, and realistic visuals are permitted. If a participant scores a high 40, the system can narrow the field of view, limit the periods of high speed, and simplify the visuals.

The cross configuration results were tested using only paired data. Improved estimates can be expected if multiple similar configurations are used to estimate the results. The models are missing a few important factors, such speed and realism. *So's* cybersickness values are likely a good measurement of these two factors, but are time consuming to produce and require a pre-built application. Using average speed, rotation, and scene complexity directly are likely to be good alternatives to using *So's* cybersickness values, but these models will need to be developed. The data used to create the ZINB model has fewer configurations to test: just 6 configurations in total with 147 sessions. However, for this type of model to be reliable, a joint pool of data from many different researchers and studies may be required.

## **6.1 Future Directions**

Our cybersickness experimentation and models have clarified the effects of several factors. An HMD's weight has little effect, assuming that there is a proper fitting display. This is of benefit



to developers as it permits them to introduce heavier hardware. Our results also support the fact that the display itself has little effect on cybersickness, and that any changes associated with the display are likely due to different factors and/or an IVB effect. This is of benefit to researchers and developers as it simplifies their experimentation. Unexpectedly, stereoscopic rendering did not show any effect on cybersickness, even when accounting for habituation. The results from the literature also present conflicting results with respect to stereoscopic rendering. The ZINB model implies that stereoscopic viewing may affect the likelihood of a participant becoming ill, but it does not predict how severe the symptoms might be if they did occur. Most likely, stereoscopic viewing has a very minor effect on cybersickness, or possibly interacts with the distance of the virtual object in the application.

While our experiments and models explain several factors, many factors remain that require further study. A list of some possibilities in this regard is available in Appendix B. Another necessary component of future cybersickness research is to find quick and easy ways to determine individual susceptibility. At two pages, the MSSQ survey used for our results is too lengthy for non-academic use. Fortunately, Golding has proposed a much shorter susceptibility test with two question grids (see Appendix A), which is associated with only a minor decrease in accuracy [144]. Surveys remain the standard measurement of cybersickness, but they are not the most accurate. We had two participants that reported clearly unusable survey results. Surveys are also likely to be skipped by participants if they delay game play. Postural stability is a viable objective alternative, but a predictive model is needed.

While the simulator sickness questionnaire (SSQ) and background demographics were the primary areas of our analysis, participants' symptoms over time, game play movements, and postural stabilities were also recorded. These data sets can be used for subsequent analysis. A participant's game play movement can be analyzed to determine how different people approach and navigate 3D environments. For example, which areas are traveled frequently versus which areas are skipped? While no formal analysis was conducted, participant immersion scores over time show one of three behaviors: no symptoms, a linear increase, or an exponential increase, with an immersion rating of 4 seeming to be the critical point. If these values could be satisfactorily correlated to a predictive postural stability model using recorded data, dynamic warning systems could be developed to warn people to exit a virtual environment several minutes before the predicted onset of cybersickness symptoms.

Cybersickness is only one aspect of a virtual environment. There is still much to be learned about navigation and interaction. Participants regularly ran into walls and became lost in our system. We had several suggestions from participants during the course of our experimentation on how to improve the system. One item of primary importance is how to include head movements into navigation. Using head movements alone is unnatural, but the participants in our study forgot which way was forward when their head movements were completely separated from the joystick's movements. The best solution to this problem is likely to include using a mix of these two types of movement.

## APPENDICES

## APPENDIX A

### SURVEY INSTRUMENTS

**Table XXIX: Simulator Sickness Questionnaire Symptom Categories**

| <i><b>SSQ Symptom</b></i>                                                         | <i><b>Weight</b></i> |                          |                              |
|-----------------------------------------------------------------------------------|----------------------|--------------------------|------------------------------|
|                                                                                   | <i><b>Nausea</b></i> | <i><b>Oculomotor</b></i> | <i><b>Disorientation</b></i> |
| <i><b>General discomfort</b></i>                                                  | 1                    | 1                        | 0                            |
| <i><b>Fatigue</b></i>                                                             | 0                    | 1                        | 0                            |
| <i><b>Headache</b></i>                                                            | 0                    | 1                        | 0                            |
| <i><b>Eyestrain</b></i>                                                           | 0                    | 1                        | 0                            |
| <i><b>Difficulty focusing</b></i>                                                 | 0                    | 1                        | 1                            |
| <i><b>Increased salivation</b></i>                                                | 1                    | 0                        | 0                            |
| <i><b>Sweating</b></i>                                                            | 1                    | 0                        | 0                            |
| <i><b>Nausea</b></i>                                                              | 1                    | 0                        | 1                            |
| <i><b>Difficulty concentrating</b></i>                                            | 1                    | 1                        | 0                            |
| <i><b>Fullness of head</b></i>                                                    | 0                    | 0                        | 1                            |
| <i><b>Blurred vision</b></i>                                                      | 0                    | 1                        | 1                            |
| <i><b>Dizzy (eyes open)</b></i>                                                   | 0                    | 0                        | 1                            |
| <i><b>Dizzy (eyes closed)</b></i>                                                 | 0                    | 0                        | 1                            |
| <i><b>Vertigo</b></i>                                                             | 0                    | 0                        | 1                            |
| <i><b>Stomach awareness</b></i>                                                   | 1                    | 0                        | 0                            |
| <i><b>Burping</b></i>                                                             | 1                    | 0                        | 0                            |
| <i>Column Weighting for Category Scores</i>                                       | <i>9.54</i>          | <i>7.58</i>              | <i>13.92</i>                 |
| <i>Total Score = 3.74 * (Sum(Nausea) + Sum(Oculomotor) + Sum(Disorientation))</i> |                      |                          |                              |

How many hours per week on average do you play console video games?

Have you ever used virtual reality before (e.g. head-mounted displays, large screen where your viewpoint is tracked, or moving platform rides, not games such as “Second Life” where the virtual reality is only experienced on a conventional computer screen)? **Y / N**

Have you ever used virtual reality with the type of device you just used? **Y / N**

How frequently do you view 3D movies or 3D TV?

Have you had any discomfort with viewing 3D movies, if so what?

How many hours per week on average do you wear hats or headbands?

Do you use glasses? Contacts? Neither? (circle)

Was there anything in particular about this virtual reality system that was causing any discomfort?

On a scale from 1 to 10, 1 being how you felt upon arrival and 10 being, 'I want to stop,' at what score would you choose to avoid using this virtual reality system?

Would you prefer a regular TV/monitor or this virtual reality system (if money was not an issue) for the following (please circle):

- |                                                                   |           |           |
|-------------------------------------------------------------------|-----------|-----------|
| a. Watching TV                                                    | <b>TV</b> | <b>VR</b> |
| b. Movies                                                         | <b>TV</b> | <b>VR</b> |
| c. Video games                                                    | <b>TV</b> | <b>VR</b> |
| d. Landmark exploration (e.g. Maps, museums, archeological sites) |           |           |
|                                                                   | <b>TV</b> | <b>VR</b> |
| e. Other (please list)                                            |           |           |

**Figure 20: Original Usability Survey**

1. How many hours per week on average do you play console video games? \_\_\_\_\_

a. If yes how many hour do you play:

First Person Shooters (i.e. Halo) \_\_\_\_\_

Platformers (i.e. Super Mario) \_\_\_\_\_

Driving (i.e. Mario Cart) \_\_\_\_\_

RPG (i.e. Final Fantasy) \_\_\_\_\_

Fighting (i.e. Street Fighter) \_\_\_\_\_

Other (Type: \_\_\_\_\_) \_\_\_\_\_

2. How many day per month, on average to you have Headaches: \_\_\_\_\_ Migraines: \_\_\_\_\_

3. Do you use Glasses? Contacts? Neither? (circle)

4. Was the nose peice comfortable: **Y** / **N**

5. Was there anything in particular about this virtual reality system that was causing any discomfort?

6. Were there any pressure points from the display? **Y** / **N**

a. If so, where: \_\_\_\_\_

7. On a scale from 1 to 10, 1 being how you felt upon arrival and 10 being, 'I want to stop,' at what score would you choose to avoid using this virtual reality system? \_\_\_\_\_

8. Would you prefer a regular TV/monitor or this virtual reality system (if money was not an issue) for the following (please circle):

|                                                                   |           |                        |
|-------------------------------------------------------------------|-----------|------------------------|
| a. Watching TV                                                    | <b>TV</b> | <b>VIRTUAL REALITY</b> |
| b. Movies                                                         | <b>TV</b> | <b>VIRTUAL REALITY</b> |
| c. Video games                                                    | <b>TV</b> | <b>VIRTUAL REALITY</b> |
| d. Landmark exploration (e.g. Maps, museums, archeological sites) | <b>TV</b> | <b>VIRTUAL REALITY</b> |
| e. Other (please list)                                            |           |                        |

**Figure 21: Revised Usability Survey**

## Motion Sickness Susceptibility Survey

This questionnaire is designed to find out how susceptible to motion sickness you are and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting. After some background questions, the questionnaire consists of two sections: Section A is concerned with your childhood experiences of travel and motion sickness, that is, before the age of 12 years. Section B is concerned with your experiences of travel and motion sickness over the last 10 years.

The correct way to answer each question is explained in the body of the questionnaire. It is important that you answer every question. Thank you for your help.

### Background Questions

1. Please State Your Age \_\_\_\_\_
2. Please State Your Sex (circle) **Male** / **Female**
3. Please State Your Current Occupation \_\_\_\_\_
4. Do you regard yourself as susceptible to motion sickness? (circle) **Not at all** / **Slightly** / **Moderately** / **Very much so**

**Section A: You childhood experience only (before 12 years of age).** For each of the following types of transport or entertainment, please indicate:

5) As a child(before age 12), how often you travelled or experiences (tick boxes):

|                             | Never | 1-4 trips | 5-10trip | 11 or more trips |
|-----------------------------|-------|-----------|----------|------------------|
| Cars                        |       |           |          |                  |
| Busses or Coaches           |       |           |          |                  |
| Trains                      |       |           |          |                  |
| Aircraft                    |       |           |          |                  |
| Small Boats                 |       |           |          |                  |
| Ships, e.g. Channel Ferries |       |           |          |                  |
| Swings                      |       |           |          |                  |
| Roundabouts: playgrounds    |       |           |          |                  |
| Big dippers, carnival rides |       |           |          |                  |

6) As a child(before age 12), how often you felt sick or nauseated (tick boxes):

|                             | Never | Rarely | Sometimes | Frequently | Always |
|-----------------------------|-------|--------|-----------|------------|--------|
| Cars                        |       |        |           |            |        |
| Busses or Coaches           |       |        |           |            |        |
| Trains                      |       |        |           |            |        |
| Aircraft                    |       |        |           |            |        |
| Small Boats                 |       |        |           |            |        |
| Ships, e.g. Channel Ferries |       |        |           |            |        |
| Swings                      |       |        |           |            |        |
| Roundabouts: playgrounds    |       |        |           |            |        |
| Big dippers, carnival rides |       |        |           |            |        |

7) As a child(before age 12), how often you vomited (tick boxes):

|                             | Never | Rarely | Sometimes | Frequently | Always |
|-----------------------------|-------|--------|-----------|------------|--------|
| Cars                        |       |        |           |            |        |
| Busses or Coaches           |       |        |           |            |        |
| Trains                      |       |        |           |            |        |
| Aircraft                    |       |        |           |            |        |
| Small Boats                 |       |        |           |            |        |
| Ships, e.g. Channel Ferries |       |        |           |            |        |
| Swings                      |       |        |           |            |        |
| Roundabouts: playgrounds    |       |        |           |            |        |
| Big dippers, carnival rides |       |        |           |            |        |

**Figure 22: Full Golding's Motion Sickness Susceptibility Questionnaire (MSSQ) [141]**

Figure 22 (cont'd)

**Section B: You experience over the last 10 years (approximately).** For each of the following types of transport or entertainment, please indicate:

8) Over the last 10 years, how often you travelled or experiences (tick boxes):

|                             | Never | 1-4 trips | 5-10trip | 11 or more trips |
|-----------------------------|-------|-----------|----------|------------------|
| Cars                        |       |           |          |                  |
| Busses or Coaches           |       |           |          |                  |
| Trains                      |       |           |          |                  |
| Aircraft                    |       |           |          |                  |
| Small Boats                 |       |           |          |                  |
| Ships, e.g. Channel Ferries |       |           |          |                  |
| Swings                      |       |           |          |                  |
| Roundabouts: playgrounds    |       |           |          |                  |
| Big dippers, carnival rides |       |           |          |                  |

9) Over the last 10 years, how often you felt sick or nauseated (tick boxes):

|                             | Never | Rarely | Sometimes | Frequently | Always |
|-----------------------------|-------|--------|-----------|------------|--------|
| Cars                        |       |        |           |            |        |
| Busses or Coaches           |       |        |           |            |        |
| Trains                      |       |        |           |            |        |
| Aircraft                    |       |        |           |            |        |
| Small Boats                 |       |        |           |            |        |
| Ships, e.g. Channel Ferries |       |        |           |            |        |
| Swings                      |       |        |           |            |        |
| Roundabouts: playgrounds    |       |        |           |            |        |
| Big dippers, carnival rides |       |        |           |            |        |

10) Over the last 10 years, how often you vomited (tick boxes):

|                             | Never | Rarely | Sometimes | Frequently | Always |
|-----------------------------|-------|--------|-----------|------------|--------|
| Cars                        |       |        |           |            |        |
| Busses or Coaches           |       |        |           |            |        |
| Trains                      |       |        |           |            |        |
| Aircraft                    |       |        |           |            |        |
| Small Boats                 |       |        |           |            |        |
| Ships, e.g. Channel Ferries |       |        |           |            |        |
| Swings                      |       |        |           |            |        |
| Roundabouts: playgrounds    |       |        |           |            |        |
| Big dippers, carnival rides |       |        |           |            |        |



Motion sickness susceptibility questionnaire short-form (MSSQ-Short)

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting

**Your childhood experience only** (before 12 years of age), for each of the following types of transport or entertainment please indicate

1. **As a child (before age 12)**, how often you **felt sick or nauseated** (tick boxes)

Your experience over the last 10 years (approximately), for each of the following types of transport or entertainment please indicate

|                             | Not<br>Applicable<br>- Never<br>Traveled | Never<br>Felt Sick | Rarely<br>Felt Sick | Sometimes<br>Felt Sick | Frequently<br>Felt Sick |
|-----------------------------|------------------------------------------|--------------------|---------------------|------------------------|-------------------------|
| Cars                        |                                          |                    |                     |                        |                         |
| Buses or Coaches            |                                          |                    |                     |                        |                         |
| Trains                      |                                          |                    |                     |                        |                         |
| Aircraft                    |                                          |                    |                     |                        |                         |
| Small Boats                 |                                          |                    |                     |                        |                         |
| Ships, e.g. Channel Ferries |                                          |                    |                     |                        |                         |
| Swings in playgrounds       |                                          |                    |                     |                        |                         |
| Roundabouts in playgrounds  |                                          |                    |                     |                        |                         |
| Big Dippers, Funfair Rides  |                                          |                    |                     |                        |                         |

t                      0                      1                      2                      3

2. **Over the last 10 years**, how often you **felt sick or nauseated** (tick boxes)

|                             | Not<br>Applicable<br>- Never<br>Traveled | Never<br>Felt Sick | Rarely<br>Felt Sick | Sometimes<br>Felt Sick | Frequently<br>Felt Sick |
|-----------------------------|------------------------------------------|--------------------|---------------------|------------------------|-------------------------|
| Cars                        |                                          |                    |                     |                        |                         |
| Buses or Coaches            |                                          |                    |                     |                        |                         |
| Trains                      |                                          |                    |                     |                        |                         |
| Aircraft                    |                                          |                    |                     |                        |                         |
| Small Boats                 |                                          |                    |                     |                        |                         |
| Ships, e.g. Channel Ferries |                                          |                    |                     |                        |                         |
| Swings in playgrounds       |                                          |                    |                     |                        |                         |
| Roundabouts in playgrounds  |                                          |                    |                     |                        |                         |
| Big Dippers, Funfair Rides  |                                          |                    |                     |                        |                         |

t                      0                      1                      2                      3

**Figure 23: Golding's [144] Short Motion Sickness Susceptibility Questionnaire**

## APPENDIX B

### DATA TABLES

**Table XXX: Literature Experiment Configurations**

| <i>Study</i>                      | <i>Condition</i>   | <i>Sickness</i> | <i>FOV<br/>(Diag.)</i> | <i>Duration</i> | <i>Sitting</i> | <i>Stereo</i> | <i>Controller</i>   | <i>Head<br/>Tracked</i> | <i>Display/IVB</i> | <i>Complexity</i> |
|-----------------------------------|--------------------|-----------------|------------------------|-----------------|----------------|---------------|---------------------|-------------------------|--------------------|-------------------|
| <b>Ours</b>                       | HMD                | 27.268          | 35                     | 24              | N              | Y             | Gamepad<br>and head | Y                       | HMD                | high              |
|                                   | Screen Size        | 21.22043        | 35                     | 24              | N              | Y             | Gamepad             | Y                       | Flat Screen        | high              |
|                                   | Large<br>Stereo    | 33.3            | 80                     | 24              | N              | Y             | Gamepad             | Y                       | Flat Screen        | high              |
|                                   | Large Mono         | 28.5            | 80                     | 24              | N              | N             | Gamepad             | Y                       | Flat Screen        | high              |
| <b>So, Ho, and<br/>Lo [15]</b>    | Low speed          | 31              | 60                     | 30              | Y              | -             | none                | N                       | HMD                | high              |
|                                   | med speed          | 33              | 60                     | 30              | Y              | -             | none                | N                       | HMD                | high              |
|                                   | High speed         | 48              | 60                     | 30              | Y              | -             | none                | N                       | HMD                | high              |
|                                   | Low<br>complexity  | 8               | 60                     | 30              | Y              | -             | none                | N                       | HMD                | low               |
|                                   | Med<br>complexity  | 29              | 60                     | 30              | Y              | -             | none                | N                       | HMD                | medium            |
|                                   | High<br>complexity | 45              | 60                     | 30              | Y              | -             | none                | N                       | HMD                | high              |
| <b>Watanabe<br/>and Ujike[43]</b> | Hill               | 45              | 360                    | 10              | Y              | Y             | none                | N                       | CAVE               | -                 |
|                                   | Plane              | 30              | 360                    | 10              | Y              | Y             | none                | N                       | CAVE               | -                 |

Table XXX (cont'd)

|                                                   |                              |                  |     |     |   |   |           |   |          |             |
|---------------------------------------------------|------------------------------|------------------|-----|-----|---|---|-----------|---|----------|-------------|
| <b>Stanney and Kennedy [145]</b>                  | Short                        | 29.44<br>(41.03) | 60  | 15  | Y | - | mouse     | Y | HMD      | -           |
|                                                   | Med                          | 20.57<br>(27.23) | 60  | 30  | Y | - | mouse     | Y | HMD      | -           |
|                                                   | Long                         | 21.93<br>(30.96) | 60  | 45  | Y | - | mouse     | Y | HMD      | -           |
| <b>Duh, Parker, and Furness [139]<sup>1</sup></b> | Bright Posture Difficulty    | .85              | 180 | 4   | N | - | none      | N | Dome/IVB | -           |
|                                                   | Dim Posture Difficulty       | 0.9              | 180 | 4   | N | - | none      | N | Dome/IVB | -           |
|                                                   | None Posture Difficulty      | 1.26             | 180 | 4   | N | - | none      | N | Dome     | -           |
| <b>Moss and Muth [29] (no handrail)</b>           | 0ms delay, 2 mag Inclusion   | 5                | 50  | 10  | N | N | none      | Y | HMD      | realistic   |
|                                                   | 0ms delay, 2 mag occlusion   | 5.5              | 50  | 10  | N | N | none      | Y | HMD/IVB  | realistic   |
|                                                   | 0ms delay, .88 mag Inclusion | 3.9              | 50  | 10  | N | N | none      | Y | HMD      | realistic   |
|                                                   | 0ms delay, .88 mag occlusion | 7.5              | 50  | 10  | N | N | none      | Y | HMD/IVB  | realistic   |
| <b>Jeager and Mourant [59]</b>                    | Treadmill                    | 15.24            | 60* | ~20 | N | - | Treadmill | N | HMD      | medium-high |
|                                                   | Mouse                        | 23.94            | 60* | ~20 | N | - | mouse     | N | HMD      | medium-high |

Table XXX (cont'd)

|                                              |                |            |     |    |   |   |          |   |                 |           |
|----------------------------------------------|----------------|------------|-----|----|---|---|----------|---|-----------------|-----------|
| <b>Toet et al.[71] Misc (SSQ-T estimate)</b> | Small          | 3.25 (60)  | 30  | 50 | Y | - | None     | N | Projection /IVB | realistic |
|                                              | Big            | 4.25 (100) | 50  | 50 | Y | - | None     | N | Projection /IVB | realistic |
| <b>Vinson et al.[107]</b>                    | -              | 25.87      | 96  | 16 | Y | N | varied   | N | Desktop/IVB     | medium    |
| <b>So and Lo [118]</b>                       | Moving         | 35         | 60  | 20 | Y | - | none     | N | HMD             | high      |
|                                              | Not moving     | 14         | 60  | 20 | Y | - | None     | N | HMD             | high      |
| <b>Ujike, Yokoi, and Saida [104]</b>         | Very small     | 3          | 13  | 20 | Y | N | None     | N | TV              | realistic |
|                                              | Small          | 3.9        | 19  | 20 | Y | N | None     | N | TV              | realistic |
|                                              | Med            | 4.5        | 28  | 20 | Y | N | None     | N | TV              | realistic |
|                                              | Large          | 8.9        | 43  | 20 | Y | N | None     | N | TV              | realistic |
| <b>Lin et al [105]</b>                       | Small          | 0.47       | 60  | 8  | Y | Y | None     | N | Car simulator   | high      |
| <b>SSQ non transformed-horizontal FOV</b>    | med            | 0.82       | 77  | 8  | Y | Y | None     | N | Car simulator   | high      |
|                                              | Large          | 1.49       | 100 | 8  | Y | Y | None     | N | Car simulator   | high      |
|                                              | x-large        | 1.65       | 180 | 8  | Y | Y | None     | N | Car simulator   | high      |
| <b>Draper et al [50]</b>                     | neutral        | 5          | 30  | 30 | - | N | head     | Y | HMD             | realistic |
| <b>Keshavarz et al. [82]<sup>2</sup></b>     | Full PW        | 9          | 60  | 18 | Y | - | None     | N | PowerWall       | realistic |
|                                              | HMD            | 3.8        | 60  | 18 | Y | - | None     | N | HMD             | realistic |
|                                              | Reduced PW     | 4          | 36  | 18 | Y | - | None     | N | PowerWall       | realistic |
|                                              | Masked PW      | 3.8        | 60  | 18 | Y | - | None     | N | PowerWall       | realistic |
| <b>Stanney et al [60]</b>                    | retraining     | 19.9       | 50  | 30 | Y | Y | mouse    | - | HMD             | -         |
| <b>Stoffregen et al. [30]</b>                | Seated close   | 101        | 77  | 50 | Y | N | Game pad | N | TV              | realistic |
|                                              | Standing close | 58.7       | 77  | 50 | N | N | Game pad | N | TV              | realistic |
|                                              | Seated far     | 60.5       | 43  | 50 | Y | N | Game pad | N | TV              | realistic |
| <b>Mehri et. a; [140]</b>                    | Seated         | 58.1       | 77  | 50 | Y | N | Game pad | N | HMD             | realistic |
|                                              | Standing       | 63.6       | 77  | 50 | N | N | Game pad | N | HMD             | realistic |

Table XXX(cont'd)

|                                                           |                    |                   |                    |                  |   |   |                |   |            |           |
|-----------------------------------------------------------|--------------------|-------------------|--------------------|------------------|---|---|----------------|---|------------|-----------|
| <b>Hakkinen, Vuori, Puhakka [61]<sup>3</sup></b>          | TV                 | 7                 | -                  | 40               | Y | N | none           | N | TV         | realistic |
|                                                           | HMD game           | 14.5              | 35.5               | 40               | Y | Y | Car simulator  | N | HMD        | realistic |
|                                                           | HMD movie          | 9.5               | 35.5               | 40               | Y | N | none           | N | HMD        | realistic |
| <b>Kolasinki and Gilson [99]</b>                          | Game               | 21.22             | 30                 | 20               | Y | Y | Mouse and head | Y | HMD        | -         |
| <b>Mourant and Thattacheny [120]<br/>SSQ-O (E. SSQ-T)</b> | City               | 15<br>(52.1)      | 60                 | 7                | Y | - | Car simulator  | Y | HMD        | high      |
|                                                           | Rural              | 9<br>(31.2)       | 60                 | 7                | Y | Y | Car simulator  | Y | HMD        | high      |
|                                                           | Highway            | 7<br>(24.3)       | 60                 | 7                | Y | Y | Car simulator  | Y | HMD        | high      |
| <b>Park et al.[56]<sup>4</sup></b>                        | Session 3          | 19.5 <sup>^</sup> | 135 <sup>^^^</sup> | 20 <sup>^^</sup> | Y | N | Car simulator  | N | TV         | medium    |
| <b>Keshavarz and Hecht [84]</b>                           | Real 3d            | 38                | 74                 | 14               | Y | Y | none           | N | Projection | realistic |
|                                                           | Real 2D            | 40                | 74                 | 14               | Y | N | none           | N | Projection | realistic |
|                                                           | Sim 3D             | 44                | 74                 | 14               | Y | Y | none           | N | Projection | high      |
|                                                           | Sim 2D             | 37                | 74                 | 14               | Y | N | none           | N | Projection | high      |
| <b>Sharples et al. [108]</b>                              | HMD                | 29.92             | 60                 | 30               | - | - | Mouse          | - | HMD        | medium    |
|                                                           | Desktop            | 15.35             | 17in               | 30               | - | - | Mouse          | - | Desktop    | medium    |
|                                                           | Theater            | 26.18             | 156                | 30               | - | - | None           | - | Projection | medium    |
|                                                           | Projection passive | 22.88             | 1725mm             | 30               | - | - | none           | - | Projection | medium    |
|                                                           | Projection active  | 11.5              | 1725mm             | 30               | - | - | mouse          | - | Projection | medium    |
| <b>Keshavarz and Hecht[146]</b>                           | Experiment 1       | 54.55             | 60                 | 18               | Y | N | none           | N | projection | realistic |

<sup>1</sup> Equipment specs were not actually reported in the study, but found in another publication presumably using the same equipment.

<sup>2</sup>A IVB enforces expected stimuli. In very familiar setting such as a virtual car, the IVB enforcing the real world is opposite of expectations.

<sup>3</sup>Although all conditions were seated, there was less physical support in the game condition.

<sup>4</sup> SSQ-T scores calculated from reported SSQ-N, D, and O. Duration shorten to reflect 15 minute break between sessions Due to the use of monitor, this system did not have the FOV-V that most systems of this width would have.

**Table XXXI: Cross Configuration Data Set**

| <b>Study</b>                          | <b>Condition</b>          | <b>Sickness</b> | <b>FOV</b> | <b>Duration</b> | <b>Seated</b> | <b>Controller</b> | <b>Head Tracked</b> | <b>IVB</b> | <b>Stereo</b> | <b>Realism</b> |
|---------------------------------------|---------------------------|-----------------|------------|-----------------|---------------|-------------------|---------------------|------------|---------------|----------------|
| <b>Ours</b>                           | HMD                       | 27.26           | 35         | 24              | N             | joystick          | Y                   | N          | Y             | high           |
|                                       | Screen Size               | 21.22           | 35         | 24              | N             | joystick          | Y                   | Y          | Y             | high           |
|                                       | Large Stereo              | 33.3            | 80         | 24              | N             | joystick          | Y                   | Y          | Y             | high           |
|                                       | Large Mono                | 28.5            | 80         | 24              | N             | joystick          | Y                   | Y          | N             | high           |
| <b>So, Ho, and Lo [15]</b>            | Low speed                 | 31              | 60         | 30              | Y             | none              | N                   | N          | N             | high           |
|                                       | med speed                 | 33              | 60         | 30              | Y             | none              | N                   | N          | N             | high           |
|                                       | High speed                | 48              | 60         | 30              | Y             | none              | N                   | N          | N             | high           |
|                                       | Low complexity            | 8               | 60         | 30              | Y             | none              | N                   | N          | N             | low            |
|                                       | Med complexity            | 29              | 60         | 30              | Y             | none              | N                   | N          | N             | medium         |
|                                       | High complexity           | 45              | 60         | 30              | Y             | none              | N                   | N          | N             | high           |
| <b>Watanabe and Ujike [40]</b>        | Hill                      | 45              | 360        | 10              | Y             | none              | N                   | N          | Y             | high           |
|                                       | plane                     | 30              | 360        | 10              | Y             | none              | N                   | N          | Y             | high           |
| <b>Stanney and Kennedy [145]</b>      | Short                     | 29.44           | 60         | 15              | Y             | mouse             | Y                   | N          | N             | high           |
|                                       | Med                       | 20.57           | 60         | 30              | Y             | mouse             | Y                   | N          | N             | high           |
|                                       | long                      | 21.93           | 60         | 45              | Y             | mouse             | Y                   | N          | N             | high           |
| <b>Duh, Parker, and Furness [139]</b> | Bright Posture Difficulty | 0.85            | 180        | 4               | N             | none              | N                   | Y          | N             | high           |
|                                       | Dim Posture Difficulty    | 0.9             | 180        | 4               | N             | none              | N                   | Y          | N             | high           |
|                                       | None Posture Difficulty   | 1.26            | 180        | 4               | N             | none              | N                   | N          | N             | high           |

Table XXXI (cont'd)

|                                                    |                                 |       |     |    |   |           |   |   |   |           |
|----------------------------------------------------|---------------------------------|-------|-----|----|---|-----------|---|---|---|-----------|
| <b>Moss and muth [81]<br/>(no handrail)</b>        | 0ms delay, 2<br>mag Inclusion   | 5     | 50  | 10 | N | none      | Y | N | N | realistic |
|                                                    | 0ms delay, 2<br>mag occlusion   | 5.5   | 50  | 10 | N | none      | Y | Y | N | realistic |
|                                                    | 0ms delay, .88<br>mag           | 3.9   | 50  | 10 | N | none      | Y | N | N | realistic |
|                                                    | 0ms delay, .88<br>mag occlusion | 7.5   | 50  | 10 | N | none      | Y | Y | N | realistic |
| <b>Jeager and Mourant<br/>[57]</b>                 | Treadmill                       | 15.24 | 60  | 20 | N | simulator | N | N | N | medium    |
|                                                    | mouse                           | 23.94 | 60  | 20 | N | mouse     | N | N | N | medium    |
| <b>Toet et al. [70] Misc<br/>(SSQ--T estimate)</b> | small                           | 3.25  | 30  | 50 | Y | None      | N | Y | N | realistic |
|                                                    | big                             | 4.25  | 50  | 50 | Y | None      | N | Y | N | realistic |
| <b>Vinson et al. [146]</b>                         | -                               | 25.87 | 96  | 16 | Y | joystick  | N | Y | N | medium    |
| <b>So and Lo [118]</b>                             | Moving                          | 35    | 60  | 20 | Y | none      | N | N | N | high      |
|                                                    | Not moving                      | 14    | 60  | 20 | Y | None      | N | N | N | high      |
| <b>Ujike, Yokoi, and<br/>Saida [104]</b>           | Very small                      | 3     | 13  | 20 | Y | None      | N | Y | N | realistic |
|                                                    | Small                           | 3.9   | 19  | 20 | Y | None      | N | Y | N | realistic |
|                                                    | Med                             | 4.5   | 28  | 20 | Y | None      | N | Y | N | realistic |
|                                                    | large                           | 8.9   | 43  | 20 | Y | None      | N | Y | N | realistic |
| <b>Lin et al [105]</b>                             | Small                           | 0.47  | 60  | 8  | Y | None      | N | Y | Y | high      |
| <b>SSQ non<br/>transformed-<br/>horizontal FOV</b> | med                             | 0.82  | 77  | 8  | Y | None      | N | Y | Y | high      |
|                                                    | Large                           | 1.49  | 100 | 8  | Y | None      | N | Y | Y | high      |
|                                                    | x-large                         | 1.65  | 180 | 8  | Y | None      | N | Y | Y | high      |

Table XXXI (cont'd)

|                                                       |                |       |      |    |   |           |   |   |   |           |
|-------------------------------------------------------|----------------|-------|------|----|---|-----------|---|---|---|-----------|
| <b>Draper et al [47]</b>                              | Neutral        | 5     | 30   | 30 | N | head      | Y | N | N | realistic |
| <b>Keshavarz et al. [83]</b>                          | Full PW        | 9     | 60   | 18 | Y | None      | N | N | N | realistic |
|                                                       | HMD            | 3.8   | 60   | 18 | Y | None      | N | Y | N | realistic |
|                                                       | Reduced PW     | 4     | 36   | 18 | Y | None      | N | N | N | realistic |
|                                                       | Masked PW      | 3.8   | 60   | 18 | Y | None      | N | N | N | realistic |
| <b>Stanney et al [58]</b>                             | retraining     | 19.9  | 50   | 30 | Y | mouse     | Y | N | Y | high      |
| <b>Stoffregen et al. [74]</b>                         | Seated close   | 101   | 77   | 50 | Y | joystick  | N | Y | N | realistic |
|                                                       | Standing close | 58.7  | 77   | 50 | N | joystick  | N | Y | N | realistic |
|                                                       | Seated far     | 60.5  | 43   | 50 | Y | joystick  | N | Y | N | realistic |
| <b>Mehri et. a; [141]</b>                             | Seated         | 58.1  | 77   | 50 | Y | joystick  | N | N | N | realistic |
|                                                       | standing       | 63.6  | 77   | 50 | N | joystick  | N | N | N | realistic |
| <b>Hakkinen, Vuori, Puhakka [59]</b>                  | TV             | 7     | 30   | 40 | Y | none      | N | Y | N | realistic |
|                                                       | HMD game       | 14.5  | 35.5 | 40 | Y | simulator | N | N | Y | realistic |
|                                                       | HMD movie      | 9.5   | 35.5 | 40 | Y | none      | N | Y | N | realistic |
| <b>Kolasinki and Gilson [100]</b>                     | game           | 21.22 | 30   | 20 | Y | head      | Y | N | Y | high      |
| <b>Mourant and Thattacheny [119] SSQ-O (E. SSQ-T)</b> | City           | 15    | 60   | 7  | Y | simulator | Y | N | Y | high      |
|                                                       | Rural          | 9     | 60   | 7  | Y | simulator | Y | N | Y | high      |
|                                                       | highway        | 7     | 60   | 7  | Y | simulator | Y | N | Y | high      |
| <b>Park et al. [54]</b>                               | Session 3      | 19.5  | 135  | 20 | Y | simulator | N | Y | N | medium    |



Table XXXI (cont'd)

|                                  |                    |       |     |    |   |       |   |   |   |           |
|----------------------------------|--------------------|-------|-----|----|---|-------|---|---|---|-----------|
| <b>Keshavarz and Hecht [85]</b>  | Real 3d            | 38    | 74  | 14 | Y | none  | N | Y | Y | realistic |
|                                  | Real 2D            | 40    | 74  | 14 | Y | none  | N | Y | N | realistic |
|                                  | Sim 3D             | 44    | 74  | 14 | Y | none  | N | Y | Y | high      |
|                                  | Sim 2D             | 37    | 74  | 14 | Y | none  | N | Y | N | high      |
| <b>Sharples et al. [108]</b>     | HMD                | 29.92 | 60  | 30 | N | mouse | Y | N | N | medium    |
|                                  | Desktop            | 15.35 | 30  | 30 | Y | Mouse | N | Y | N | medium    |
|                                  | Theater            | 26.18 | 156 | 30 | N | None  | Y | Y | N | medium    |
|                                  | Projection passive | 22.88 | 80  | 30 | Y | none  | N | Y | N | medium    |
|                                  | Projection active  | 11.5  | 80  | 30 | Y | mouse | N | Y | N | medium    |
| <b>Keshavarz and Hecht [147]</b> | Experiment 1       | 54.55 | 60  | 18 | Y | none  | N | Y | N | realistic |

**Table XXXII: Some Factors that Require Further Study**

|                               |                                   |                                                       |                                                             |
|-------------------------------|-----------------------------------|-------------------------------------------------------|-------------------------------------------------------------|
| 1. Long term Habituation loss | 2. Gestural Navigation            | 3. Orientation only versus 6DOF head tracking         | 4. Head movements                                           |
| 5. Color                      | 6. Postural Pre-exposure          | 7. Severity of the vision correction                  | 8. Vertical versus horizontal cues                          |
| 9. Percentage of real world   | 10. Postural monitoring           | 11. Time of day                                       | 12. Time of day (group by day versus night person)          |
| 13. Contrast                  | 14. Stopping speed (acceleration) | 15. Analytical/details versus global/whole perception | 16. Sensor drift acceptance                                 |
| 17. Swivel chair navigation   | 18. calibration                   | 19. Rotation speed                                    | 20. Other IVB (e.g. icons)                                  |
| 21. Screen luminance          | 22. Vertical field of view        | 23. Individually adjusted gain                        | 24. Percentage of time actively interacting with the system |

## APPENDIX C

### TERMINOLOGY AND DEFINITIONS

*Accommodation* - the eyes' adjustment of the lens' focal length to the perceived distance.

*Augmented reality (AR)* - any simulated environment whose visual content is partially produced by a computer and the appearance of the environment changes according to the participant's behavior.

*Coefficient of determination ( $R^2$ )* - the proportion of variability or variance that a model explains.

*Computer Aided Virtual Environments (CAVE)* - three or more large screens with head tracking. What is sometimes referred to as a one-wall CAVE is considered to be just a large screen and is sometimes called a PowerWall.

*CPois( $x, \lambda$ )* - The continuous variant of the Poisson function.

*Degrees of Freedom (DOF)* - the number of axes of translation and rotation when navigating a virtual environment.

*Field of view (FOV)* - the subtended angle an object fills in a visual field.

*Heterophoria* - the extent that one eye moves away from vergence after the other eye is covered.

*Immersion* - the time spent inside a virtual environment.

*Independent Visual Backgrounds (IVB)* - visual stimuli that enforce real world expectations.

*Motion History Questionnaire (MHQ)* - a questionnaire to determine a past history of motion sickness.

*Motion Sickness Susceptibility Questionnaire (MSSQ)* – a questionnaire to determine a past history of motion sickness and susceptibility.

*Our HMD* - refers to our experiment that compared a lightweight HMD to a heavy HMD.

*Our Screen* - refers to our experiment that compared a small screen to a large screen, but held the field of view and standing position constant.

*Our Render* - refers to our experiment that compared a monoscopic application to a stereo application.

*Simulator Sickness Questionnaire (SSQ-T/N/D/O)* - a standard cybersickness measurement. SSQ refers to the questionnaire, SSQ-T refers to the total score, SSQ-N refers to the nausea score, SSQ-D refers to the disorientation score, and SSQ-O refers to the oculomotor score.

*Vergence* - the eyes' movement to focus on the same object.

*Virtual environment (VE)* - any simulated environment whose visual content is at least partially produced by a computer and the appearance of the environment changes according to the participant's behavior. VE include both virtual and augmented reality.

*Virtual reality (VR)* - a simulated environment whose visual content is entirely produced by a computer and the appearance of the environment changes according to the participant's behavior.

*Zero Inflated Negative Binomial (ZINB)* - a statistical distribution model that includes a model .

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