

Early Prediction of Cybersickness in Virtual, Augmented & Mixed Reality Applications: A Review

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Abstract - The field of Virtual, Augmented & Mixed Reality (VAMR) has already taken up the consumer market by storm and are demanding among users owing to their practicality and aesthetics. Despite the massive popularity and hype, VAMR carry a loathsome side-effect called “Cybersickness”, which is often times severe enough to cause significant discomfort to the users causing the discontinuation of use. Research have been going on for years with the intentions of finding the theories and factors which contribute to this unpleasant experience but we are in no way shape to determine the underlying contrivances of cybersickness. There are systems to quantify and measure cybersickness but a symptom prediction tool which can be used by application developers to evaluate their products for cybersickness susceptibility is non-existent. This paper presents a summary of literature and provides a review and a discussion with the intentions of deriving a predictive algorithm which would ultimately address the research gap and missing links.

Keywords – *cybersickness, virtual reality, computer-vision, human-computer-interaction*

I. INTRODUCTION

Over the past few decades, the way people interact with computers has changed drastically [1]. There had been numerous attempts over the years to bridge the human-computer barrier with the ultimate goal of making the human-computer interactions as natural as possible. The most novel idea was the thought of using hands as a device to connect and communicate with computers mimicking human to human interactions [2]. It is safe to say that this has been achieved with the invention of digital reality systems also known as Virtual, Augmented & Mixed Reality (VAMR) systems.

The field of VAMR is rapidly blooming as a result of the massive popularity of new generation smart devices such as displays, hand-held devices and wearables. VAMR is working towards the reduction of cognitive load minimizing the human-computer interaction efforts. These systems offer immersion to the users diminishing attention shifts [3].

Despite of the popularity, there is an abundance of issues when it comes to all three technologies. Most of these issues are common across the platforms and research has been going on for a long time trying to tackle them. The most prominent problem that stands out has to be the concerns regarding the user experience (UX). It has been discovered that VAMR systems cause a nasty side effect called “Cybersickness” which directly obstructs the UX forcing the user to terminate the session instantly [4].

Cybersickness has persisted throughout the existence of VAMR systems [5] and as a result, a large population are

unable to take advantage of this technology. Researchers are busy finding the causes and the user response to cybersickness but only a handful of people are working on to prevent or predict the occurrence of cybersickness.

II. METHODOLOGY

A wide variety of literature was analysed to gather knowledge and insight on the symptoms, theories and contributing factors of cybersickness. The already existing approaches of measuring and predicting cybersickness were critically appraised giving more priority to recently published research. The discovered evidence will be presented in a narrative manner through the upcoming sections.

III. CYBERSICKNESS

The term “Cybersickness” was proposed by McCauley and Sharkey (1992) [6] and it was described as the interim side-effects caused by virtual reality immersion. Cybersickness exhibits similarities to motion sickness and simulator sickness and it's often categorised as a form of motion sickness [7]. But the major discrepancy when comparing these phenomenon is the user's state of motion. In cybersickness, the user is stationary for the most part but experiences self-motion sensations as a result of the moving imagery [8]. This sensation is commonly referred to as Vection.

From a physiological standpoint, human body is not in a position to cope cybersickness and according to researchers at Coventry University, up to 80% of the population experience some form of cybersickness [9], [10].

A. Symptoms

VAMR experiences can induce an array of symptoms associated with cybersickness. Following are some commonly identified side-effects and symptoms [8], [11], [12].

1. Eye strain
2. Nausea
3. Headache
4. Excessive Sweating
5. Dryness of mouth
6. Fullness of stomach
7. Vertigo
8. Ataxia
9. Vomiting

10. Dizziness
11. Disorientation
12. Fatigue
13. Strange hand eye coordination

The above symptoms can occur during and post exposure and the majority of these side-effects are temporary whereas few can linger for hours [13] or days [14]. As a result, many virtual experience providers recommend users to limit themselves from attempting risky activities such as driving for at least an hour after exposure to VAMR.

B. Theories

Over the years, several research groups have identified three major explanatory theories for the existence of cybersickness.

Sensory Conflict Theory is the oldest and the most accepted theory among the three [15]. It claims that VAMR is likely to cause mismatches between the vestibular and visual inputs of the human body and these discrepancies can lead to cybersickness related symptoms such as nausea, headaches and other oculomotor disturbances [16], [17]. However the theory falls short in explaining the reason for the users to be sick due to these cue conflicts [8].

Poison/ Intoxication Theory tries to base the explanations for the occurrence of cybersickness from an evolutionary standpoint. According to Treisman (1977) [18], when the human body experiences abnormal coordination of the visual, vestibular, and other sensory inputs, the nervous system mistakes these circumstances with poison digestion and responds by emptying the stomach. This corporal response of the nervous system can cause symptoms like nausea, vomiting and discomfort.

Postural Instability Theory was developed by Riccio and Stoffregen and it states that the human body always tries to maintain stable posture in the environment and the unexpected changes to the environment could result in the loss of postural control [19].

All these theories provide compelling arguments but further research needs to be conducted to confirm the validity of these claims.

C. Contributing Factors

Apart from the theories discussed above, there are three main categories of factors that influence the intensification of cybersickness. Namely, Hardware & Software factors, Individual Differences and Environmental Factors [8].

Hardware & Software Factors

Issues related to hardware & software had been a huge bottleneck at the dawn of the VAMR industry but fortunately, they have improved quite a until then [20]. But there are few outstanding issues that are left to be addressed.

Oftentimes virtual reality (VR) tech suffers from position tracking errors. Inconsistencies in tracking could register unstable information resulting in jitter. Jitter has a tendency to cause dizziness and lack of concentration [21].

Head mounted displays (HMD) usually takes a bit of time to update users visual feed in response to the head movements.

This delay is commonly referred to as “Lag” and has a tendency to cause unsettling sensations which result in cybersickness symptoms [22].

Flicker is another issue and the perception of flicker will differ from person to person and the likelihood increases with the increase of field of view (FOV). Flicker will cause eye fatigue [23] and could be reduced by increasing the framerate of the visual feed.

Individual Differences

Susceptibility to cybersickness hugely depend on individual factors such as health, behavioural conditions, age, race, ethnicity etc. [24]. Oftentimes individual differences are overlooked when considering contributing factors of cybersickness but research suggests that these shouldn't be disregarded [25]–[27].

Environmental Factors

Environmental conditions such as temperature, relative humidity, light, air quality, ambient noise etc. can aid to cybersickness during a VAMR experience. These conditions aren't so easy to control due to their unpredictable nature [24].

IV. EXISTING WORK

Cybersickness is not a new phenomenon [24] and the concerns about it had paved the way for a rich body of literature over the years. Its studies can be dated back decades since VAMR has a broad spectrum of applications ranging from home entertainment to military [28]. As stated in the above section, cybersickness has a diverse range of symptoms. Researchers have been using a wide verity of approaches and measures to detect and rate the severity of these cybersickness symptoms [29]. These approaches can be mainly categorised in to four sections.

1. Questionnaire based approaches
2. Postural Instability based approaches
3. Physiological/ Biometric approaches
4. Predictive Model based approaches

Questionnaires were the first attempts made to rate and quantify symptoms in simulators and these approaches tend to lean towards simulator sickness and motion sickness rather than cybersickness. On the contrary, postural instability related approaches were inspired by the postural instability theory in the recent years. Some have attempted to measure physiological signals and biometrics in order to predict the onset of cybersickness where as others have taken a predictive model based approach. All these four categories are explained in detail below.

A. Questionnaire based approaches

Kennedy et al. (1993) [30] utilized a 28 symptom version of the Pensacola Motion Sickness Questionnaire (MSQ) which was originally developed by Kellogg et al. (1964) [31] and conducted an extensive research by analyzing more than 1000 sets of previous data and came up with a 16 term measurement method to quantify cybersickness (see Figure 1). Their main objective was to demystify the similarity concept of motion sickness and simulator sickness and to point out the need for a distinguished index for measuring simulator sickness severity. Potential research subjects were subjected to the “Simulator Sickness Questionnaire” (SSQ) pre and post exposure to simulations. The questionnaire identified issues

such as disorientation, oculomotor effects, and nausea and the total score at the end reflected the severity of simulator sickness experienced by the users. SSQ is widely applied in the research studying the propensity of inducing cybersickness and simulator sickness.

Although SSQ is the primary measure of cybersickness symptoms [11], it was never intended to be used in the context of virtual reality. And to make matters even worse, it was devised 25 years ago. As a result of the above mentioned issues, SSQ has received quite a bit of criticism over the years. There have been many attempts during the past to revise and refactor the SSQ.

<i>MSQ Symptom</i>	<i>Retained for SSQ</i>	<i>Eliminated for SSQ</i>
General discomfort	X	
Fatigue	X	
Boredom		X
Drowsiness		X
Headache	X	
Eyestrain	X	
Difficulty focusing	X	
Increased salivation	X	
Decreased salivation		X
Sweating	X	
Nausea	X	
Difficulty concentrating	X	
Depression		X
Fullness of head	X	
Blurred vision	X	
Dizziness (eyes open)	X	
Dizziness (eyes closed)	X	
Vertigo	X	
Visual flashbacks		X
Faintness		X
Awareness of breathing		X
Stomach awareness	X	
Decreased appetite		X
Increased appetite		X
Desire to move bowels		X
Confusion		X
Burping	X	
Vomiting		X

Figure 1. Symptoms in MSQ & SSQ [30]

Kim et al. (2004) [32] came up with a revised version of the SSQ claiming that the original SSQ was missing several key symptoms and lacked interpretability. The new scale was named Revised-SSQ (RSSQ) by the team and consisted significant changes to the measuring criteria and the scale. They ditched the original 4 option ordinal response scale and opted for an 11 option scale with two labels at the two extremes. Despite the efforts RSSQ didn't replace the original SSQ mainly because of its intimidating scale and the under-representative study group.

Bouchard et al. (2007) [33] attempted to refactor the SSQ with the intentions of making it specific to cybersickness. They were convinced that the SSQ had multiple subfactors which resulted in a biased total score and expressed their concerns regarding the use of military pilots in the SSQ development study arguing the applicability to general adult population. To address these problems, they used a non-military study group to avoid cross-loading and devised a new questionnaire with two main categories: nausea and oculomotor. Although a higher portion of females were used in the study, many researchers argued that the study sample was still unrepresentative. As a result of the above mentioned concern, the usage of this refactored version has been limited [29].

Bruck and Watters (2011) [34] tried to incorporate physiological responses to the factor structure of the SSQ by using respiration and heart rate as variables alongside the

original 16 symptoms of the SSQ. The sample size used in the study was better in terms of gender representation but had received some negative remarks due to its limited size. And the use of a principal components analysis (PCA) rather than a common factor model has been criticised by some researchers [11]. Same as the other refactoring attempts, there's no evidence to prove that this version is significantly better than the original.

Ames et al. (2005) [35] designed a refactored version of the SSQ called Virtual Reality Symptom Questionnaire (VRSQ) to be distinctively used in the context of virtual reality. A seven option response scale with four descriptive labels was utilized in the VRSQ and unlike SSQ, VRSQ was intended to be specifically used for the measure of cybersickness. However, VRSQ has not been validated in the context of virtual reality and the methodology followed during the study is questionable mainly due to the use of a non-interactive video feed on a HMD [11]. Hence the measure has received very little attention.

Stone III (2017) [11] did a psychometric evaluation of the SSQ and pointed out the need for an empirical measure for cybersickness. He further argued that the use of the SSQ in the context of virtual reality to be problematic and stated that the refactored versions failed to provide an obvious advantage over the original version. The study resulted in a new measure called Cybersickness Questionnaire (CSQ), a two factor exploratory model with a different factor structure and scoring mechanism. What is noteworthy about this new measure is its ability to be collaboratively used with the SSQ. According to Stone III (2017) [11], researchers have the opportunity to administer the original SSQ if they wish and use the CSQ's scoring criteria afterwards.

The use of single-item measures instead of the SSQ have been a common practice lately since the longer questionnaires usually take a lot of time to carry out requiring for frequent breaks which might result in diminished cybersickness symptoms [29]. Majority of these scales required the user to rate their feelings of either nausea, motion sickness, or discomfort throughout the course of the study at regular intervals. **Nalivaiko et al. (2015)** [36] used a single-item, 11 option nausea rating scale in their study with labels "0-no signs of nausea" and "10-ready to vomit" at corresponding extremes. **Rebenitsch and Owen (2014)** [37] utilised an immersion rating in their study and continuously inquired the participants to rate the experience on a scale of 0 - 10. This method ensured the safety of the participants and they reportedly discontinued the exposure if anyone responded "10". Although these single-item scales are adequate to monitor cybersickness symptoms, they are not as sensitive or informative as the SSQ and its refactored versions [29].

B. Postural Instability based approaches

The core concept behind the postural instability theory is that the maintenance of body posture is crucial and prolonged instability of posture may lead to visually induced motion sickness (VIMS) [19]. Some of the VIMS symptoms are drowsiness, dizziness, fatigue, pallor, cold sweat, oculomotor disturbances, nausea, and vomiting [38]. The aforementioned symptoms are very similar to that of Vection and the relationship between Vection and VIMS had been questioned and debated over the years in the literature [39]. This approach sounds convincing on paper since it doesn't require to bother the user during the simulation and most importantly due to its objective nature. But in practice this approach seemed to

violate the above advantages simply because of the standardized stance requirement [29].

Researchers at the University of Waterloo are reportedly working on defining a predictive model to identify the likelihood of cybersickness in individuals by analysing their postural swaying patterns as a response to moving visual field. According to the research team, knowing who might be susceptible to cybersickness beforehand would help in minimising the dawn of symptoms [40].

Dennison & Zmura (2017) [39] devised an experiment to test out the link between postural sway and cybersickness. They exposed a group of standing and seated HMD wearing test subjects to a visual feed of a virtual tunnel that rotated along their line of sight. It was discovered that only a minority of the group exhibited postural sway in response to the commencement of the tunnel rotation. The increase of the rotational speed of the tunnel directly resulted in increase of cybersickness. The duo claimed that the subjects who exhibited greater levels of cybersickness, showed less variations in postural sway.

C. Physiological/ Biometric approaches

Cybersickness symptom prediction using physiological signals and biometrics have received a noticeable interest in the past mainly due to the availability of affordable medical technology. Several research groups have pointed out prospective physiological consequences of cybersickness from time to time [5], [41], [42]. And by following this approach, researchers are able to gather evidence of symptoms without intruding the user. Heart rate and blood pressure measurements are commonly used for analysis [29] but some research groups have managed to expand their horizons by integrating different physiological signals such as brain activity, skin reaction etc.

Kiryu et al. (2007) [43] used electrocardiogram (ECG), blood pressure and respiration in their study to figure out the trigger factors and accumulation factors in cybersickness. The power frequencies of the physiological signals were used in estimating the sensation intervals and the onset of cybersickness.

Kim et al. (2005) [42] examined 16 electrophysiological signals of 61 test subjects over a period of 9.5 minutes. Three susceptibility questionnaires were obtained pre-exposure and the physiological signals were recorded before, during and after the immersion. The SSQ was administered at the end of the exposure for the test subjects to report their cybersickness severity. They were able to figure out a strong positive correlation between cybersickness and gastric tachyarrhythmia, eye blinking rate, heart rate and EEG.

Dennison & Zmura (2017) [5] examined ECG, electrogastrogram (EGG), electrooculogram (EOG), photoplethysmogram (PPG), breathing rate and galvanic skin response (GSR) in their study to figure out the feasibility of using physiological signals to predict cybersickness. Apart from the physiological measures, they administered the SSQ and asked the users to verbally rate the cybersickness severity every two minutes. The main purpose of using the SSQ in the study was to figure out the possibility of predicting sickness scores on the SSQ by using the physiological changes. And they were able to find significant correlations in the SSQ scores and physiological signals.

D. Predictive Model based approaches

Use of a predictive model to predict cybersickness seems highly constructive but upon close examination of the literature, it was found that only a handful have even attempted the said approach in their studies.

Design Interactive is a tech company based in the United States and they have been studying cybersickness for over two decades. They have been able to develop a predictive algorithm which uses both the questionnaire & physiological approaches in unison [44]. Unfortunately, Design Interactive only provides services to their exclusive clientele. Therefore the algorithm is not publicly available.

Bockelman and Lingum (2013) [24] have pointed out the need for a cybersickness prediction tool & indicated their interest in working towards an open source tool to predict the possibility of cybersickness. They further reported that they have been working on a predictive model to provide guidance to virtual reality users. But the success rate or the progress of the research is unknown.

V. ANALYSIS OF EXISTING WORK

By conducting a comprehensive investigation, we were able to distinguish the pros and cons of each study and most importantly we were able to eliminate the unlikely factors that could potentially cause cybersickness to avoid any over fitting issues.

A. Analysis of the existing questionnaires

The original version of the SSQ exhibits substantial differences in comparison to the revised and refactored versions with regards to the context it was intended to be used, number of items in the questionnaire and the factor model. Table 1 depicts a comparison between the original SSQ and its refactored versions.

	Study					
	Kennedy et al. (1993)	Kim et al. (2004)	Bouchard et al. (2007)	Bruck and Watters (2011)	Ames et al. (2005)	Stone III (2017)
Intended Context	SS	SS	CS	CS	CS	CS
Number of Items	16	24	16	18	13	9
Factor Model	3	4	2	4	2	2

* SS – Simulator Sickness, CS - Cybersickness

Table 1. Comparison between the existing questionnaires

B. Analysis of the physiological signals

Table 2 displays a brief analysis of some important physiological measures and their correlation to cybersickness.

Physiological Signal	Definition	Correlation to Cybersickness
Blood Pressure	The pressure between heart beats	High
Electrocardiogram (ECG)	Monitors the heart	High

Electroencephalogram (EEG)	Monitors electrical activity due to current flow in the brain	Medium
Electrogastrogram (EGG)	Detects stomach movement and strength	High
Electrooculogram (EOG)	Detects the movement of the eye	Non-existent
Galvanic Skin Response (GSR)	Monitors changes in electrical resistance of the skin	Non-existent
Respiration (RSP)	Monitors inhalation of oxygen	High

Table 2. Physiological signals and their correlation to cybersickness

C. Analysis of the Individual Differences affecting cybersickness

Table 3 depicts an analysis of the individual factors taken from cybersickness specific researches.

Factor	Correlation to Cybersickness	Reasoning
Age	High	Young subjects proved to be more susceptible
Gender	Medium	Females appeared to be more susceptible
Ethnicity	Low	Not tested for cybersickness
Experience	High	Repeated immersion decreases cybersickness susceptibility
Concentration Level	Medium	Diminished concentration likely reduces cybersickness
Postural Instability	High	Unstable posture leads to cybersickness
History of Illnesses (Headaches, Motion Sickness, Migraines, Dizziness)	High	History of illness would likely increase the likelihood of cybersickness
BMI	Medium	BMI has proven to have a minor effect on cybersickness

* BMI – Body mass index

Table 3. Analysis of individual differences

D. Analysis of Software and Hardware factors

Table 4 presents a summary of the prospective software and hardware factors which affects cybersickness.

Hardware	Software
Lag	Flicker
Frame rate	Colour
Field of view (FOV)	Scene complexity
Head Tracking	Realism

Table 4. Summary of Hardware & Software factors affecting cybersickness

VI. DISCUSSION

The ultimate goal of this study was to review the current status of cybersickness research with the intentions of deriving a predictive algorithm for cybersickness susceptibility. During the study we realised that the performance of the already

existing approaches on their own were subpar and the use of a hybrid approach seemed to be a highly versatile option.

In many cases, individual differences and software & hardware factors had not been taken in to consideration. Some of these factors have proven to be highly correlated with cybersickness, hence ditching these would not be a smart idea. Any new approach should take leverage of the existing work and should carefully consider all the possible contributing factors. On the other hand, machine learning and deep learning is on the rise and the use of the said technologies would enhance the results of the solution significantly.

VII. CONCLUSIONS & FUTURE DIRECTIONS

Overall, Regardless of the realism or interactive abilities, current VAMR systems are not usable for a prolonged period of time and they are a risk to the users because of cybersickness.

The primary focus has been given to finding the underlying reasons of cybersickness and VAMR's predisposition of inducing cybersickness but cybersickness prediction has received very little to no attention. However, upon close inspection of literature, it has been identified that only subjective analysis is often used in cybersickness studies and the current primary measure of cybersickness (SSQ) is massively outdated. Whereas, other than subjective factors, there are a numbers of possible contributing factors impacting cybersickness which are often overlooked.

While exploring the literature, we strongly felt the need for an all-round predictive model and through the analysis of the existing work, we were able to identify the key factors and parameters necessary for deriving such an algorithm. With the gathered knowledge, we hope work towards a predictive algorithm which can be used by the application developers to check their products for cybersickness susceptibility prior to release.

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