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# A Roller Coaster for the Mind: Virtual Reality Sickness Modes, Metrics, and Mitigation

Dalton C. Sparks
*University of Louisville*, dalton.sparks@louisville.edu

# A Roller Coaster for the Mind: Virtual Reality Sickness Modes, Metrics, and Mitigation

Dalton C. Sparks[1]

[1] The University of Louisville, Louisville, KY, USA

**ABSTRACT**

Understanding and preventing virtual reality sickness(VRS), or cybersickness, is vital in removing barriers for the technology's adoption. Thus, this article aims to synthesize a variety of academic sources to demonstrate the modes by which VRS occurs, the metrics by which it is judged, and the methods to mitigate it. The predominant theories on the biological origins of VRS are discussed, as well as the individual factors which increase the likelihood of a user developing VRS. Moreover, subjective and physiological measurements of VRS are discussed in addition to the development of a predictive model and conceptual framework. Finally, several methodologies of reducing VRS by improving VR hardware and software are covered.

**KEYWORDS:** Virtual Reality, Virtual Reality Sickness, cybersickness, virtual reality sickness mitigation, virtual environments

## INTRODUCTION

The influence of Virtual Reality, or VR, technology is rapidly growing. By 2028 the market size is estimated to increase nearly 800 percent to reach a market size of 252 Billion United States Dollars (The Insight Partners). The ability to immerse a user into a realistic virtual environment has numerous implications for a variety of industries. This unique trait of VR allows technology to be implemented for diverse use cases in manufacturing (Berg & Vance, 2016), medicine (Mazurek et al., 2019), tourism (Yung & Khoo-Lattimore 2017), and numerous others. With these in mind, VR's versatility has it poised to become a mainstay throughout the world.

However, a major limiting factor to the growth and acceptance of VR is virtual reality sickness (VRS) (Chang et al., 2020), often called cybersickness (LaViola, 2000). This form of visually induced motion sickness can result in a variety of symptoms associated with classical motion sickness, including eye strain, headache, nausea, vomiting, and a variety of other unwanted side effects (LaViola, 2000). Thus, this discomfort can have a significant impact on the user experience of those using VR and, in extreme cases, could prevent a user from having a pleasant experience within a virtual environment altogether. Moreover, the widespread nature of VRS is a major contributing factor to the severity of the issue. In previous studies, the incidence of VRS ranged from "22 to 80 percent of participants(Kim, H. et al., 2021, p. 1) and resulted in an average dropout rate of 15.6 percent across 46 experiments(Saredakis et al., 2020, p. 5). To this end, numerous academic articles have been published to classify, analyze, and address the issue of cybersickness within VR. This review aims to examine a variety of academic publications on the modes in which cybersickness manifests, the metrics by which it is judged, and the methods of mitigation that could reduce its effects on users.

## MODE

The fundamental causes of VRS are debated among various scholars. To avoid over-specification, the interchangeable terms VRS and cybersickness are used generally to discuss "any sickness caused using VR, irrespective of the specific cause of that sickness" (Guna et al., 2019, p. 264). Moreover, the generality of the term is indicative of the variety of causes and theories believed to contribute to the phenomena. Thus, discussion on the causes of VRS mainly focuses on two areas: its biological origin within the human body and the individual and systems factors that affect its severity.

## THEORIES ON THE ORIGIN OF VRS WITHIN HUMAN BIOLOGY

The main result of cybersickness is the occurrence of vection, "the impression of self-motion under certain conditions"(LaViola, 2000, p. 49). This originates in the human visual and vestibular systems, which coordinate to provide information on movement and acceleration

(p. 50). Thus, these two systems play important roles in the appearance of VRS within individuals. From this, cybersickness is proposed to stem from three theories: the sensory conflict theory, the poison theory, and the postural instability theory.

The sensory conflict theory is the "most common theory" (MacArthur et al., 2021, p. 2). It asserts that incongruence between the vestibular and visual systems results in cybersickness. This is amplified when outside stimuli do not match a person's expectations. For example, when these systems do "not get the expected response, a conflict occurs and cybersickness may ensue" (LaViola, 2000, p. 50). However, this theory is limited due to the impossibility of measuring "the level of conflict between senses and physiological expectations of an individual(Shafer et al.,2017,p. 5). Moreover, the theory does not account for "why some individuals get sick and why others do not, given a set of identical stimuli" (LaViola, 2000,p. 51).

In contrast to the sensory conflict theory, the poison theory poses VRS in an evolutionary context. The theory proposes that the effects of cybersickness stem from the body's natural response to ingesting a poisonous substance, such as vomiting(Shafer et al., 2017, p. 4), which involves the aforementioned systems (p. 51). Furthermore, when the body is placed in a virtual environment, it affects the "visual and vestibular system in such a way that the body misreads the information and thinks it has ingested some type of toxic substance"(p. 51). Similar to the previous theory, it lacks predictive power and does not account for why different people have different reactions to the same stimuli.

Finally, the postural instability theory (PIT) asserts that the VRS is a direct result of "prolonged postural instability" (Howard & Van Zandt, 2021, p. 1224). This postural instability is a result of "feeling that one is not in control of their own motion"(Shafer et al., 2017,p. 4). Thus, the theory proposes that "mismatches between perceptions and expectations of visual and vestibular cues are the cause of postural instability" (p. 1224) and, therefore, cause VRS. In recent years, "cumulative findings have caused a paradigm shift towards greater acceptance of PIT" (p. 1225). It provides a method by which multiple sources of VRS can be explained. However, critics propose that it is possible that "postural instability and motion sickness are only common outcomes of sensory conflict" (p. 1225).

## SYSTEM AND INDIVIDUAL FACTORS IMPACTING VRS

While these theories address the fundamental source of VRS, various factors have been observed to amplify the risk of sickness during VR use. Chang et al. (2020) organizes these causes into hardware, content, and human factors.

Hardware factors stem from the intrinsic properties of the VR device utilized. Chang et al. (2020) recognize hardware factors such as display type, hardware field of view, latency of actions, and screen factors. As these factors relate to the level of technological development, "with time technology improves so many of these problems could go away in the future"(LaViola, 2000, p. 52).

Chang et al. (2020) refer to content in terms of technical details of the software. Specifically, they state that the optical flow of scene stimuli, graphic realism, reference frame of fixed visual stimuli, content field of view, duration, and controllability can be considered to result in cybersickness. Moreover, the genre of experience, such as an action-oriented or calm environment, within VR can influence VRS. Guna et al.'s(2019) study found that, when comparing cybersickness in a beach environment to a roller coaster, there are "clear differences in the participants' VR sickness response regarding the video content type"(p. 272).

The third set of factors, human or individual factors, is the most difficult to classify. Chang et al.(2020) list that they are composed of age, gender, prior VR experiences, and motion sickness susceptibility. Howard & Van Zandt (2021) amend this list by adding amount of rest, neurological disorder, real-world experience, technological experience, immersive tendencies, visual acumen, psychological disorder, and relevant phobias. However, after experimental evaluation, Howard & Van Zandt (2020) could only support six of the previous factors: motion sickness susceptibility, gender, neurological disorder, real-world experience, technological experience, and relevant phobias(p. 1237). This implies that specific factors may only be significant in specific scenarios and must be considered contextually.

With this in mind, the impact of gender on VRS susceptibility is of special interest for future research. Both Chattha et al. (2020, p. 130494) and Howard & Van Zandt (2021, p. 1237) experimentally determine that women are more likely to experience cybersickness than men. Moreover, MacArthur et al. (2021) systematically reviewed VR research articles, discovering that "women may be disproportionately affected by negative symptoms of cybersickness" (p. 1). Ironically, this predisposition makes it more difficult to improve women's VR experience through research. This is a result of the finding that "women were consistently recorded as more likely to discontinue participation in the experiment due to intensity of cybersickness" (p. 9). This indicates that special care may have to be taken when addressing gendered issues in VR research.

## METRICS

In order to determine the impact of the aforementioned factors, it is important to create and derive a set of metrics that can be utilized in research. In this vein, classical subjective and physiological measurements are utilized to gather empirical data in various studies (Shi et al., 2021; Monteiro et al., 2021; Ohyama et al., 2007). Moreover, efforts are being taken to develop VRS prediction models (Kim, J. et al., 2018) and conceptual frameworks (Chattha et al., 2020).

## MEASUREMENTS

VRS measurement techniques are vital in determining the severity and nature of cybersickness in research studies. Thus, a variety of subjective and objective measurement techniques have been established to be utilized in experimentation.

One of the most popular techniques titled the Simulator Sickness Questionnaire(SSQ) (Kennedy et al., 1993), traces its lineage back to the earlier Motion Sickness Questionnaire. Kennedy et al. (1993)'s questionnaire, composed of a weighted calculation of 16 relevant sickness symptoms, has been monumentally influential in a variety of studies; as of 2022, it has been cited more than 4500 times (Google Scholar 2022)

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Although SSQ was intended for usage with computer simulations, such a flight simulations, its implementation has been adapted to suit researchers' needs. Particularly, variations can be found in how it is scored, when the questionnaire is administered, and the level of detail reported.(Bimberg et al., 2020, p. 465) Moreover, some negative aspects of the SSQ need to be taken into account before implementation. Particularly, the original paper utilizes a misleading formula, non-uniform scaling of values, a military reference population, a lack of baseline scores, and the reliance on subjective ratings.(Bimberg et al., 2020, p. 465) Thus, efforts have been made to introduce a more specialized Virtual Reality Sickness Questionnaire (Kim, H.K. et al., 2018). Moreover, physiological measurements are also important for analyzing VRS. Chang et al.(2020) list several key measures as postural sway, heart rate variability, skin temperature, electrocardiogram, and eye-related measures.

## PREDICTION AND CONCEPTUALIZATION

Beyond measurement, other efforts are being taken to adequately represent VRS through qualitative and quantitative means. For example, being able to predict when cybersickness will occur given a set of input stimuli. In one case, Kim, J. et al. (2018) worked to create a VR sickness prediction model capable of reliably estimating physiological responses associated with VRS. This model utilizes human head movement and the perception of the scene as inputs. Additionally, the model can be extended to cover more factors in the future. Likewise, Chattha et al. (2020) worked to create a conceptual framework for motion sickness (p. 130489). This framework visualizes several contributing factors to VRS in addition to their impact and the subjective and objective measures utilized to analyze the level of VRS experienced. The framework was then empirically evaluated, accepting all but one of their proposed hypotheses. Developing these metrics to their fullest extent can provide researchers with valuable tools to model the occurrence of cybersickness.

## MITIGATION

Ultimately, the end goal of investigating and measuring VRS is to reduce and mitigate it for users. Although recent hardware improvements have alleviated many of the traditional issues of screen flicker, tracking error, and latency (LaViolla, 2000), many sources of cybersickness are still present in virtual environments. To avoid these, VR designers must make informed choices to mitigate sickness. Additionally, it may be necessary for VR users to formulate strategies to mitigate VRS themselves.

## DESIGN CHANGES

A variety of methods have been developed to guide developers in how they may mitigate cybersickness. Although a variety of methods exists, several prominent methods include changing the mode of locomotion (Monteiro et al., 2021), changing how visual content is displayed (Shi et al, 2021), and improving both graphical fidelity (Chang et al., 2020) and audio-visual stimuli congruence (Kim & Lee, 2022).

How users move in virtual environments is a very important aspect of the development of cybersickness. The most well-known locomotion technique for VRS mitigation is "teleport." (Monteiro et al., 2021) This method allows users to immediately move from one place to another without in-between motion. For example, the user is able to point directly at a location in a virtual environment and, by pressing a button, relocate instantly to the selected location. This contrasts with then sliding movement seen when utilizing a trackpad or analog stick to move directly. The discrete change of location seen in teleportation reduces disorientation and helps to prevent cybersickness (Monteiro et al., 2021).

Visual mitigation techniques involve changing how content is displayed to users. Three popular methods are field of view (FOV) reduction, depth-of-field (DOF) blur, and rest frame (Shi et al., 2021). The addition of field of view reduction involves limiting the amount of visual content in a user's periphery, thus decreasing the risk of vection (p. 3). However, limiting the view may result in decreased immersion for the user (p. 3). Implementing depth-of-field blur involves rendering the virtual environment such that the visual content is gradually blurred out from the center, simulating the focusing behavior of the eye (p. 4). Hussain et al. (2021 were able to utilize this "biologically inspired spatial blur"(p. 20) to reduce the risk of cybersickness. The third method, the rest frame method, implements a central fixed rest frame so that users may have a constant point of reference with a virtual environment (Monteiro et al., 2021). Although these methods are capable of reducing VRS, their overuse or poor implementation can result in loss of information and user discomfort (Shi et al., 2021).

Chang et al. (2020) propose that the graphical fidelity and its interaction with multisensory stimuli can result in various degrees of cybersickness. Moreover, they evaluate this claim with an experimental procedure, finding that, in conjunction with a high level of graphical fidelity, "multisensory information might be required to reduce the level of discomfort" (p. 1679) This indicates that designers must work on matching different sensory inputs. Particularly, "the congruence between audio-visual stimuli has an essential effect on VR experience as a multisensory integration condition" (Kim & Lee, 2022, p. 2088). This implies that special care must be taken by designers to align both the auditory and visual sensory inputs in Virtual Reality.

## USER ACTION

While designing out the possibility of cybersickness is preferable, the user may have to find ways of mitigating cybersickness themselves. One method to do so relates to the process of increasing parasympathetic nervous activity through controlled diaphragmic breathing (Russel et al., 2014). As the usage of virtual does not result in a change in parasympathetic nervous activity (Ohyama et al., 2007), the body's natural methods of naturally addressing motion sickness are not activated (Russel et al., 2014). Thus, through specialized breathing techniques, the parasympathetic nervous system can be activated, resulting in decreased VRS (Russel et al., 2014). Moreover, as studies demonstrate that users with VR experience are less likely to have cybersickness (Howard & Van Zandt, 2021; Hussain et al., 2021), one solution may be for users to gradually adjust to the virtual environment through regular immersion until they achieve full adaptation.

## CONCLUSION

The study and mitigation of VRS is imperative in helping the technology reach mainstream prominence. As long as a portion of the population is consistently afflicted by cybersickness, there will be massive barriers to widespread use. Currently, much research is being conducted on how to best categorize, measure, and avoid cybersickness. Through researching its causes, a better understanding of why symptoms occur can be obtained. Understanding the origins and various factors that result in cybersickness is the first step in ascertaining how to mitigate it. Moreover, the development of metrics that allow VRS to be measured, predicted, and conceptualized provides valuable tools for gaining insight into these origins. From this, developers can find and implement methods that reduce VRS and maximize the user experience for everyone, surmounting one of the central issues which has plagued virtual reality since its inception.

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