Virtual Reality Sickness: A Review of Research on Sickness and Nausea Induced by Virtual Reality

Isaac Jang

Abstract

Virtual reality sickness (VRS), VR-induced nausea, or cybersickness all refer to a common side effect of using head-mounted virtual reality devices. Symptoms are similar to those of traditional motion sickness, and are thought to have the same underlying cause of conflict between the visual and vestibular systems. This report reviews research on individual factors underlying differences in susceptibility to sickness, technical aspects of software and hardware that affect sickness, possible mitigation techniques, and future research directions. It also provides a brief overview of modern, consumer-facing head-mounted VR devices released since 2015 which are commonly used in research.

Introduction

Virtual reality sickness, or VRS, is a collection of physical conditions and sensations similar to motion sickness. Symptoms include nausea, vomiting, headache, sweating, pallor, eye strain, and disorientation. Similar to motion sickness, it is generally accepted that VRS is caused by conflict between one's visual and vestibular systems. While the symptoms can be similar or identical to those of motion sickness, VRS is distinguished from motion sickness by the possibility of occurring as a result of perceived visual self-motion (LaViola 2000). In other words, while motion sickness generally occurs when motion is felt by the body but not matched by what one sees, VRS occurs when one sees motion without feeling it.

VRS has the potential to be a significant obstacle for the widespread development and acceptance of VR by the broader public. Previously confined to research labs and R&D departments, head-mounted VR systems have increased in popularity with gamers and early adopters within the past decade. Accompanying this rise in popularity is a rise in reports of nausea and sickness. When the Oculus Rift Developer Kit 1 was released, reports of nausea were widespread, with some users creating a forum dedicated to "Rift Sickness" (Orsini 2016). At the 2016 Game Developers Conference, one journalist reported that after testing various VR Games for several hours, they felt "disoriented, a touch nauseous, and distinctly headachey" (MacDonald 2016). Outside of anecdotal reports of sickness, two major gaming publishers (Electronic Arts and Take-Two) have publicly stated their concerns that nausea and sickness would slow adoption of VR gaming among the public (Orland 2014). Even the former CEO of Oculus, Brandon Iribe, admitted that when using the developer kit versions of the Rift, he had “gotten sick every time I’ve tried it. Every time until recently” (Orsini 2016). Evidently, the incidence of nausea and sickness is significant enough to cause concern both within the industry and by proponents of VR in general.

A number of different terms have been used to refer to VRS over the years, including “Simulator Sickness” or “Cybersickness”. “Simulator Sickness” has traditionally been used to refer to the distinct phenomena of motion sickness induced by aircraft simulators, but has been used interchangeably with VRS. As the term “Virtual Reality” itself is in some cases used to refer to various simulator technologies, the distinction remains unclear. “Cybersickness” appears to apply solely to VR technologies and as a result is used interchangeably with VRS, particularly in the past two decades.

Modern VR Devices

Throughout this article, references will be made to “Modern VR”, referring to the generation of consumer-facing virtual reality devices developed since 2010. Most notable and well-known among these devices are the Oculus Rift, HTC Vive, and Playstation VR (formerly known as Project Morpheus). These devices can be roughly categorized together based on a horizontal resolution of around 1080 pixels, a refresh rate of 90Hz, and an FOV of around 100-110 degrees. Furthermore, they require a computer with relatively high-end dedicated graphics or a gaming console. A number of other lower-cost devices have been developed around the same time, some of which are reliant on user’s smartphones for the technology, such as Google’s Daydream View or Samsung Gear VR. Other devices, such as the Oculus Quest, incorporate mobile-level processing hardware into the headset itself.

	Oculus Rift (CV1)	**HTC Vive**	**Playstation VR**
Resolution (per eye)	1080x1200	1080x1200	960x1080
Refresh Rate	90 Hz	90 Hz	90 - 120 Hz*
Field of View	110 degrees	110 degrees	100 degrees
Launch Date	March 2016	April 2016	October 2016
Launch Price	$600	$799	$399

*While headset supports native 120Hz refresh rate, content is often rendered at 60fps with motion interpolation.

Individual Factors Linked to Susceptibility

There are several factors which are shown to affect one's susceptibility to VRS. The most well supported of these factors appears to be the sex of the user. In an experiment using the Oculus Rift DK-2 (Developmental Kit 2), significant differences in motion sickness rates were shown to be a function of gender by way of sex differences in postural stability (Munafo et. al. 2017). This finding is congruent with previous research into sex differences in susceptibility to motion sickness in general and simulator sickness in particular (Park et. al. 2006). Postural stability itself has been investigated, with increased postural stability associated with lower sickness rates (Munafo et. al. 2017). Other research has identified sex differences in field of view as a factor contributing to VRS susceptibility. Because flicker tends to be more perceptible in the periphery of one's field of view, the general pattern of women having a wider field of view can contribute to an increased likelihood of flicker perception among women, and thus sickness rates (LaViola 2000).

Age is another factor contributing to one's susceptibility to VRS. Previous research has found that susceptibility is highest between ages 2 and 12, decreasing significantly from age 12 to 21, then more slowly thereafter (LaViola 2000). However, more recent work suggests that older adults over the age of 50 are more susceptible to VRS than younger adults (Park et. al. 2006). The question of whether differences between age groups are due to perceptual factors or due to behavioral differences in VR environments has yet to be determined.

Finally, according to LaViola illnesses can contribute to VRS, citing research that identifies fatigue, sleep deprivation, hangover, upset stomach, emotional stress, head colds, flu, ear infection, or upper respiratory illness as conditions contributing to VRS (2001).

Technical Factors of Software and Hardware Affecting VRS

Many technical aspects of a VR system can affect the onset of VRS. The implementation of sophisticated head and hand motion tracking in modern VR systems introduces yet more factors beyond the display-oriented factors explored in older literature. One such factor is the degree to which head motions are visually compensated by the device. Both "proper" compensation of head movements and no compensation at all appear to result in equivalent levels of sickness, but an inverse compensation (i.e. the virtual environment moving in the opposite direction of the head movement) resulted in significantly higher rates of sickness (Palmisano et. al. 2017). An equally high level of sickness was found when head movements were properly compensated with a delay of ~290ms relative to motion input. These results are consistent with some previous research showing that the presence of input lag as a result of slower processor speeds had an effect on both disorientation and nausea (Cobb et. al. 1999). However, Moss and Muth found no difference in sickness rates between 0ms and 200ms of additional lag (2011). They speculate that the base level of delay inherent to that particular HMD was enough to induce some level of sickness, similar to that of the 200ms delay condition.

In addition to motion inputs and lag, technical aspects of a headset's optics and display influence VRS. There is significant evidence linking field-of-view (FOV) with sickness rates. One experiment using a simulator device found significantly higher rates of sickness for a 180° simulator experience relative to a 60° one (Seay et. al., 2001). In the same study, participants noted that the high-FOV condition was the more immersive experience of the two, suggesting that increases in FOV result a tradeoff between immersion and VRS rates. Lin et. al. also found that FOV and sickness were linked, with sickness ratings increasing as FOV was increased from 60 degrees to 100 degrees and 140 degrees (2002). They also found that engagement and immersion ratings (collectively referred to as "presence") were positively correlated with FOV, consistent with the findings from Seay et. al..

Related to FOV is the visibility or occlusion of the external environment. Moss and Muth found that occluding peripheral vision of the external environment when using an HMD resulted in increased sickness rates (2011). The authors speculate that preventing the user from receiving optic flow information in the periphery generates more sensory conflict between the visual and vestibular systems, than if the external environment were visible in the periphery.

Fidelity and realism has also been shown to influence VRS rates: based on a limited comparison of two virtual roller-coaster rides, increased detail and graphic realism appears to be associated with higher rates of VRS (Davis et. al. 2015).

The design of the virtual software in use can also influence VRS via the type of physical interaction required. Davis et. al. also identified forcing head movements as another explanation for higher rates of VRS in their roller-coaster comparison (2015). By forcing the user to turn their head to the left and then forwards in order to restart the experience, the design of the virtual interface may be more sickness-inducing. Sharples et. al. found that participants not in control of their movement in a virtual environment experienced significantly higher levels of oculomotor and sickness symptoms, relative to participants controlling their own motion (2008). As noted by the authors, this is consistent with previous research exploring user control. The authors attribute this to the unexpected nature of the differences in sensory input (sensory conflict theory) leading to increased sickness. Collectively, these findings have important implications for developers of virtual environments, which are discussed in the next section.

Mitigation techniques

Over the decades, some techniques for mitigating VRS have been explored. The least sophisticated method is repeated exposure to the VR experience. In a study with 30 participants, Regan found significant reductions in VRS symptoms over four separate immersions in a VR environment, with over half of the participants ceasing to report symptoms between the first and fourth immersion (1995). Cobb et. al. found that sickness symptoms reduced to negligible levels after just two immersions (1999). These results suggest that careful construction of a VR experience is necessary to find the right balance between an experience that allows users to stay in the environment for too long (resulting in severe sickness) and an experience that limits users to a short period of time each day to acclimate them.

These findings, while informative, may not offer much to those seeking to reduce sickness levels during a user's very first exposure to VR, particularly in those cases where the experience is so negative as to turn off the user from VR forever. In the same study, the authors speculate that first-time use often involves more head movements due to the novelty of trying a head-tracking device. If supported, this idea suggests that careful design of virtual experiences during tutorials is necessary to prevent users from engaging in excessive head motions during first time experiences of VR.

Different interaction and control schemes can play a role in allowing different head movements and thus influencing VRS rates. As discussed earlier, virtual interface design choices requiring more head motions could lead to increased rates of sickness. Developers of virtual experiences and environments have also adopted a number of techniques over the years which reportedly reduce sickness rates. One strategy is to "ground" the user by placing them inside a vehicle interior or cockpit, a technique used by the developers of Eve:Valkyrie (Lang 2016). Another technique being used is to embody the user's nose, arms, and legs in the virtual environment (Samit 2018). One novel approach is to replace hand controller inputs with head/torso movement, so that by leaning slightly forwards the user moves forwards in the virtual environment (Samit 2018). Because this method of interaction mimics the way people tilt their heads and torsos when walking, it may reduce conflict between body motion and expected visual input. This method is similar to the march-in-place method of motion control explored by Lee et. al., who found that such a method resulted in lower rates of VRS than hand motions or using controller inputs (2017). Other similar techniques used by developers include restricting user movement by implementing teleportation inside the virtual environment, or by using zero-gravity environments to simulate a smoother and more linear experience of motion (Statt 2016).

Both teleportation and embodiment of hands, body, and helmet have been shown to result in decreased sickness rates, relative to controller inputs and lack of embodiment respectively (Zaidi and Male 2018).

As discussed earlier, Moss and Muth found that occluding the peripheral vision of an HMD resulted in increased sickness rates (2011). This finding suggests that allowing users to see real life environments in the periphery while using an HMD would decrease sickness rates; however, this technique would obviously come at a cost to immersion.

Moss and Muth also found that before introducing the use of a handrail, participants using the HMD exhibited “extreme responses”, such as severe confusion and disorientation (2011). They note that participants exhibited symptoms similar to vasovagal syncope (drop in heart rate and blood pressure leading to fainting, resulting from a shocking or stressful experience), and that grasping a handrail may also have increased their postural stability, decreasing rates of sickness. They conclude that “users should not stand freely when using an HMD”, and that “Users should be provided with something to enhance postural support” (pg. 317). Of course, the advent of motion-tracked hand controllers in modern VR services precludes the possibility of grasping onto stable objects like handrails; however, other methods of enhancing postural support such as requiring a seated position may reduce sickness levels.

Finally, technical aspects of the HMD hardware discussed earlier play a role in influencing VRS rates. As discussed earlier, input lag on the scale of ~290ms resulted in significantly higher levels of sickness. Incidences of judder/stutter (momentary instances of noticeable lag) on the scale of several hundred milliseconds must be minimized or eliminated. Additionally, as increasing resolution and graphical fidelity comes at the cost of frame rates, developers of virtual environments and headset displays must balance these factors to avoid causing judder and lag.

Future Research Directions

One question with the potential for further investigation is the degree to which prior research on motion sickness induced via various interactive devices can be applied to modern virtual reality devices. There is a significant body of research into motion sickness induced by older simulator technologies, otherwise known as simulator sickness. While such results are informative, further research could investigate differing factors between traditional simulators and modern HMD’s using the same high-fidelity environments made possible by today’s computing power. For example, future research might look at the effect of the lenses used in modern VR devices, for example, comparing them to the experience of looking at the multiple displays of a flight simulator.

A number of exciting new consumer-facing VR technologies are in development or have just been released, with significant implications for VRS research. For example, the Oculus Rift S (released 2019), intended to be a successor to the Oculus Rift (CV1, released 2016), has significantly higher resolution at 1280x1440 per eye, compared to 1080x1200 for the CV1 (Machkovech 2019). However, the display refreshes at a lower 80hz, relative to CV1's 90hz refresh rate, likely in an effort to counterbalance the increased computing demands of the higher resolution. Future research could examine the interaction between these higher resolutions, refresh rates, and VRS. The Valve Index (released 2019), capable of up to 144hz refresh rate with a resolution of 1440x1600 per eye and FOV of ~130 degrees, opens up the possibility of investigating VRS with cutting-edge display technologies incorporated into a system compatible with existing modern VR ecosystems and virtual environments (Machkovech 2019).

	Oculus Rift S	**HTC Vive Pro**	**Valve Index**
Resolution (per eye)	1280x1440	1440x1600	1440x1600
Refresh Rate	80 Hz	90 Hz	90 - 144 Hz
Field of View	~110 degrees	110 degrees	~130 degrees*
Launch Date	May 2019	April 2018	June 2019
Launch Price	$399	$799 (Headset only)	$999

*Valve has not released official FOV figures for the Index, only stating that it is about 20 degrees more than than existing headsets (Machkovech 2019).

Currently, little research has been conducted using this class of devices. There is at least one media report of an individual using the Valve Index at 90hz for more than 30 minutes without VRS symptoms, when the same individual had suffered from sickness when in the same virtual environment using the HTC Vive (Sebastian 2019). Future research involving the Index might investigate the link between its increased refresh rates, FOV, and resolution, and VRS. The displays found inside the Index also reportedly offer sub-pixel persistence, effectively eliminating persistence blurring; this is in contrast to the Vive's 2-3 pixel blurring when viewing moving elements. Future research might look at this factor of current and upcoming HMD displays.

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