Reducing Simulator Sickness for Travel in Virtual Reality

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ABSTRACT

This review highlights our current understanding of simulator sickness, which is similar to motion sickness, as it relates to travel in virtual reality (VR). In this review we discuss the underlying physiological causes of simulator sickness, the relationship between virtual environment design and simulator sickness as well as various models for locomotion in VR. The underlying physiological cause of simulator sickness is not yet proven with cue conflict theory[22], the mismatch between the visual-vestibular senses, and long term memory mismatches[33], the mistmatch between the senses and learned behavior, being the most widely accepted. Locomotion techniques[4] are reviewed. Controller-based techniques are affordable but offer reduced levels of presence and an increased likelihood of experiencing simulator sickness. Room scale-based techniques have large spatial requirements but offer increased levels of presence. Motion-based techniques, whilst expensive, offer higher levels of presence in situations where space is an issue.Lastly teleportation methods, whilst cheap, offer reduced levels of presence and high likelihood of experiencing simulator sickness. Special attention is given to haptic feedback devices and their ability to reduce simulator sickness. Research on this topic is scarce and provides an opportunity for further investigation into the matter.

KEYWORDS

Virtual Reality, Simulator Sickness, Virtual Environments, Haptic Feedback

1 INTRODUCTION

According to Steuer[41], "Virtual Reality (VR) is a real or simulated environment in which a person experiences a sense of being, either through natural or mediated means". With the availability of virtual reality head mounted displays (HMD) like the Oculus Rift or the HTC Vive, VR is becoming increasingly popular. Valve's Steam store reported that the number of users with VR headsets had doubled in 2018[14]. VR serves other purposes outside the commercial realm, for example, it has applications in therapy[45] and medical training[12].

The rise in popularity of VR has challenged the way we design virtual environments (VE) as the design principles of applications rendered on traditional displays are not applicable to VR applications. Additionally, traversing the virtual environment in VR presents a set of problems not found in traditional applications, for example, traversing a virtual environment in VR can cause simulator sickness (SS). Simulator sickness, a subset of motion sickness, is diagnosable by symptoms such as nausea, headache, general discomfort and eye-strain[18]. Simulator sickness decreases a user's enjoyment and is a significant negative factor in flight simulator training[19] and virtual therapy[3].

The purpose of this literature review is to highlight our current understanding of simulator sickness as it relates to motion in VR. Section 2 reviews theories that seek to identify the underlying physiological causes of simulator sickness as well as factors that trigger simulator sickness. Section 3 discusses how certain environment design decisions can trigger simulator sickness. Section 4 highlights methods of measuring simulator sickness and section 5 discuses the various models of locomotion in VR.

2 CAUSES AND TRIGGERS OF SIMULATOR SICKNESS

2.1 Causes

There are numerous theories as to why the brain induces motion sickness. This review will discuss three of those theories: "poison" theory, cue conflicts and long term memory conflicts. It should be noted that none of these theories have been proven or disproven.

2.1.1 Poisoning. In 1977 Treisman[43] attempted to provide an evolutionary explanation for motion sickness. Treisman theorized that motion sickness arised due to our evolutionary need to protect against ingesting toxins and symptoms like nausea and malaise occur as a way to train our body to avoid ingesting similar toxic substances in the future. To support his theory Treisman argued that because motion sickness exists in numerous other vertebrate species, such as fish, cats and dogs, there had to be a biological reason for motion sickness to exist. Treisman notes that infants, young puppies and animals with highly specialized diets do not suffer from motion sickness given that they are unlikely to encounter toxins. Morrow[28] notes that Treisman's theory is also consistent with observations that people who are more susceptible to motion sickness are more likely to suffer from nausea and vomiting when exposed to toxins in chemotherapy.

2.1.2 Cue Conflict. Cue conflict, the mismatch between sensory inputs, is the most widely accepted cause of motion sickness[22]. Most commonly occuring between the visual and vestibular senses, simulator sickness arises when the input of one or more senses conflicts with the input of another. Duh et al.[11] found that lower frequency conflicts between visual-vestibular senses were more likely to cause simulator sickness than conflicts at higher frequencies. Draper et al. [10] queried image scale in virtual environments, their results suggest image scale is a provocative factor in inducing simulator sicknessas as it causes visual-vestibular conflicts. Prothero et al.[32] suggest an alternative to the cue conflict theory, they theorize simulator sickness does not occur from conflicting motion cues but rather the rest frames selected from those motion cues. They support this by showing that the presence of an independent visual background, which heavily influences rest frames, reduces simulator sickness.

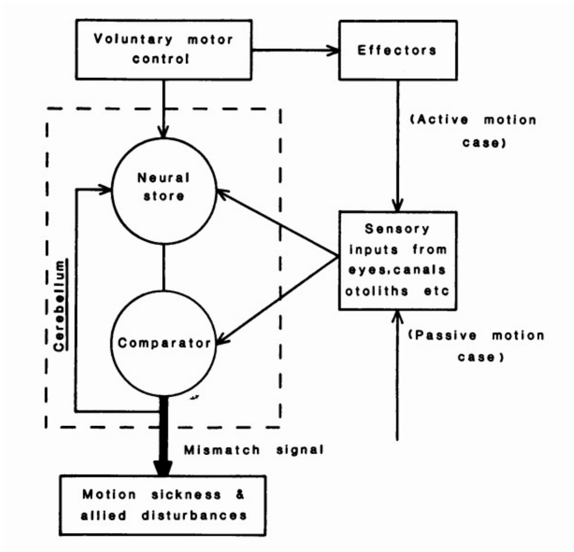

Figure 1: Neural Mismatch Model proposed by Reason[33]

2.1.3 Long Term Memory Conflicts. This theory, also known as the neural mismatch theory, is similar to the cue conflict theory, but instead of sensory mismatches, it involves the mismatching of balance signals and learned behaviour. This theory implies that simulator sickness can be unlearned. Kohl[21] argues that conflicts between sensory inputs and long-term memory are more likely to cause motion sickness. Reason[33] proposes a model for the neural mismatch theory (Figure 1) and Kennedy et al.[20] supports this theory by demonstrating how individuals are capable of adapting to the adverse effects of motion sickness through repeated exposure in flight simulators.

2.2 Triggers

2.2.1 Eye-Strain. Eye-strain, also known as asthenopia, manifests itself by non-specific symptoms such as pain around the eyes and blurred or double vision. Eye-strain is caused by the straining of the ciliary muscle inside the iris and the overworking of the brain. The ciliary muscle allows us to focus on objects at varying distances and prolonged focus on objects that are too small or too near can cause eye-strain. In the context of simulator sickness, Mourant et al.[29] note that oculomotor symptoms, which includes eye-strain, are the most common symptoms of simulator sickness. Lampton et al.[23] note that eye strain is the most common symptom of simulator sickness displayed in participants after extended periods of time in a virtual environment.

2.2.2 Vection. Vection is the illusion of self motion. It occurs when the visual senses are entirely responsible for the sense of motion and is integral to the cue conflict theory. Hettinger et al.[15] notes that experiencing vection is polarizing. All of their participants experienced either no vection or significant amounts of vection. They also note that 80 % of the participants that experienced vection also experienced simulator sickness suggesting that there is a high correlation between sensory conflicts and simulator sickness. Interestingly, Bonato et. al.[5] found that constant vection can actually enhance the presence one feels within VR but can also induce simulator sickness depending on the individual. They also noted that variable vection (ie: apparent acceleration) significantly exacerbated simulator sickness when compared to constant vection.

3 ENVIRONMENT DESIGN DECISIONS AND SIMULATOR SICKNESS

3.1 Environment Fidelity

Graphical fidelity has been a large focus of commercial video games over the past decade, with each subsequent game trying to one-up the other. However, VR represents a totally different experience. In VR latency greatly affects a user's presence[26] as well as the likelihood of suffering from simulator sickness[17]. This is unfortunate because in order to simulate 3D vision, virtual environments have to be rendered twice, once for each eye. Therefore, graphical fidelity is more challenging than in traditional graphical applications, resulting in more rendering effort and potentially greater latency. Fortunately research[25] suggests that graphical fidelity is not a major requirement for presence (See Section 3.3).

3.2 Objects within a Virtual Environment

Virtual Environments are constructed from a number of objects. These objects not only have a visual representation but they also have properties that influence the way we perceive them. For example, a boulder is heavy and a feather is light. These properties are influenced by learned behaviour[34] and should affect the way virtual environments are designed. If virtual objects do not behave in accordance with a user's expectations or implicit understanding of how to interact with an object, it causes a cognitive dissonance known as postural instability. This is especially true for objects in motion. Hosking et. al.[16] demonstrated that our perception of objects in motion, particularly when directed toward us, is partially based on learned characteristics. This is important because, as Dichgans et al.[8] notes, mismatches in object motion and learned behaviour can cause postural instability.The number of objects in motion should also be taken into account as this can cause sensory conflict and sensory overload. Sensory overload can cause many of the same symptoms as motion sickness. Prothero et al.[32] suggest the use of an independent visual background (Figure 2) to help reduce the side-effects of vection as it allows a person to position themselves relative to a fixed reference point.

3.3 The Uncanny Valley

The uncanny valley describes the unsettling feeling one may feel when looking at an object that closely but not perfectly resembles that of its real world counterpart. Whilst this theory is common when talking about humanoid robots, it can also occur when looking at dolls and upon viewing computer generated faces in both movies and video games[37]. Brenton et. al.[7] present four working hypotheses associated with the uncanny valley, two of which will be highlighted in this review. The first hypothesis is the "Break in Presence" hypothesis ,coined by Slater[38], it describes the conflict that occurs between two ideas in the brain: "This is a human" and

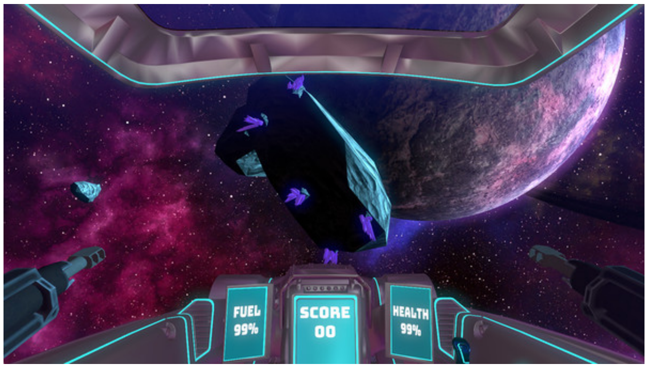

Figure 2: Captain 13 Beyond the Hero [1], a VR take on the classic asteroids game. The developers used planets as independent visual backgrounds to reduce simulator sickness

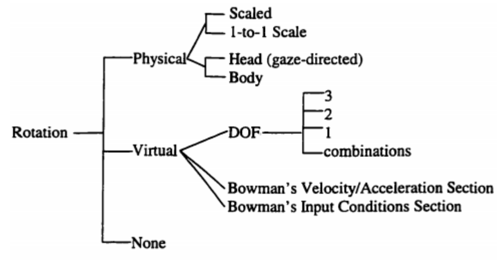

Figure 3: Arns'[2] taxonomy for rotation

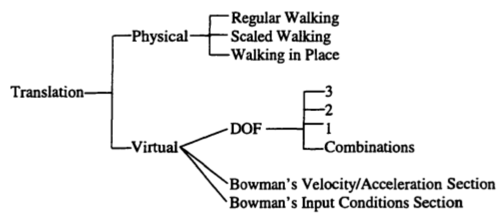

Figure 4: Arns'[2] taxonomy for translation

"This is not a human". When this conflict occurs, a break in presence occurs and as this continues the unsettling feeling of the uncanny valley arises. The second hypothesis is the "Expectation" hypothesis, it describes the decreasing ability to suspend our disbelief as the realism of an object increases. Think back to Tom & Jerry, a cartoon in which a cat and mouse continuously find absurd ways to injure each other. We suspend our disbelief because the characters are cartoons. However, if these acts were to be performed by realistic characters in a realistic environment with the same outcome, the "Expectation" hypothesis says that we would struggle to suspend our disbelief thus finding the situation implausible.

In the context of VR and simulator sickness, the two hypotheses discussed provide useful insight into the design of virtual environments. They indicate that graphical fidelity may negatively affect overall presence in a scene. This is important not only for the overall enjoyment of VR games but in fields of research, such as emotional psychology or simulator sickness, the results of an experiment may be affected by the graphical fidelity of a virtual environment.

4 MEASURING SIMULATOR SICKNESS

4.1 Simulator Sickness Questionnaire(SSQ)

The SSQ was developed by Kennedy et al.[18] as a necessary reduction of the Motion Sickness Questionnaire(MSQ). After collecting pre and post exposure MSQs for 1119 individuals. 12 of the original 28 symptoms were deemed statistically insignificant when attempting to diagnose simulator sickness. The remaining 16 symptoms were grouped into three distinct categories: oculomotor (eye-strain, blurred vision headache, etc.), disorientation (dizziness, vertigo, etc.) and nausea (nausea, increased salivation, burping, etc.). Symptoms on the SSQ are self-identified and a short scale from 0-3 is used for each one. The symptom scores are then weighed and summed and an overall sickness score is obtained.

4.2 The Immersive Tendency Questionnaire (ITQ) and Presence Questionnaire (PQ)

Designed by Witner et. al.[46], the ITQ and PQ is one of the most cited papers in VR literature. The ITQ seeks to identify the tendency of an individual to feel immersed and serves as pre-experiment questionnaire to determine the likelihood of a participant experiencing presence, whilst the PQ seeks to measure the degree to which individuals feel immersed and is taken post-experiment. The ITQ and PQ are subjectively reported on by individuals and the results of the ITQ and PQ are used in conjunction to measure presence experienced.

5 LOCOMOTION IN VR

5.1 A Model for Locomotion

Because vection is the most significant contributor to simulator sickness, psychological intervention seems the most reasonable approach to reducing simulator sickness. Numerous models for locomotion in VR have been proposed. Bowman's taxonomy[6] separates locomotion into three categories: direction selection, velocity selection and input conditions but is rather broad and does not take into account a user's mode of transportation. Arns[2] extends Bowman's taxonomy by adding additional modes of transportation based on the technology available. She separates rotation (Figure 3) and translation (Figure 4) and further subdivides those categories into virtual and physical components. Arns' taxonomy, while complete in 2002, does not take modern VR technology into account. Boletsis[4], attempting to create a new model for locomotion for modern-day VR, designed a typology based on 36 relevant articles. This typology (Figure 5) identifies 11 techniques for locomotion categorised into one of the following locomotion types:

5.1.1 Motion-based. Locomotion techniques that support continuous motion and employ physical movement to enable interaction fall into this category. Techniques such as gesture-based motion, redirected walking and walking-in-place fall into this type. These techniques often rely on additional hardware and software to track and simulate movement. In the case of walking-in-place, treadmills

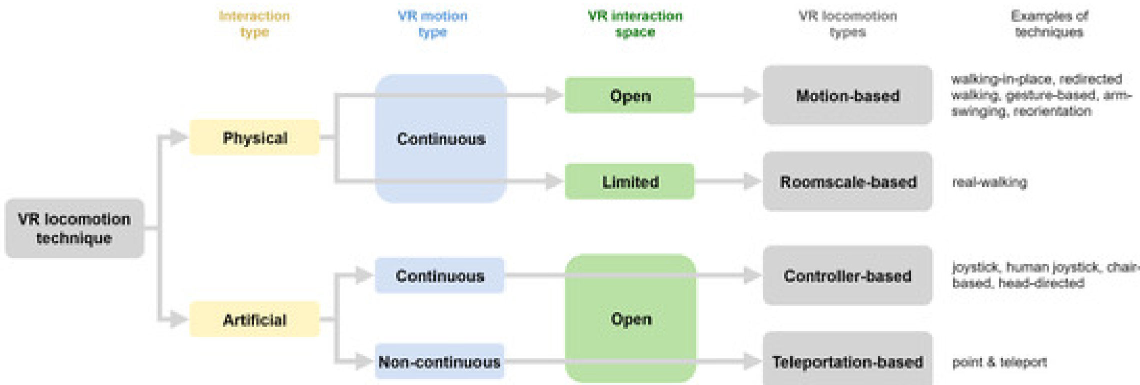

Figure 5: Boletsis' [4] model for locomotion in VR

and stepping machines can be used while gesture-based motion can be tracked with additional sensors. Interestingly, redirected-walking is implemented differently to the other techniques in this category as it mismatches the users' real and virtual environments in an attempt to scale a large world into a confined space[30].

5.1.2 Room scale-based. These locomotion techniques are used when the virtual environments size is limited by the real environments size. These techniques also employ physical movement to enable interaction. For example, real-walking is one of these techniques. A user moves freely about a limited space and their position is usually tracked using their HMD or additional sensors.

5.1.3 Controller-based. These techniques involve a user utilizing a controller to artificially move around an environment. The environment is open and the motion continuous. Example techniques include, joysticks and head-direction motion.

5.1.4 Teleportation-based. Techniques under this type artificially teleport a user from one location to another. The movement is non-continuous and can appear disorientating to a user. Point-and-teleport is the most common technique in this category and has been successfully implemented by heavily controlling when and where teleportation can take place.

5.2 Haptic Feedback Devices

Haptic feedback provides a user with a sense of touch when interacting with a virtual environment. It has been shown that haptic feedback greatly improves presence[35] and has shown promise in medicine[42], chemistry[13] and robotics[9]. However, not much research has been done to identify the effect haptic feedback has on simulator sickness.

6 DISCUSSION

There are numerous theories that try to explain why humans and other veterbrate species suffer from motion sickness. Three of theses theories were highlighted in this review. The 'poison' theory, while popular pre-2000s, has been subjected to heavy criticisms. Oman[31] discredits this theory stating the general absence of vestibular symptoms after poison-consumption by humans and animals does not support Triesman's model. Cue conflict is the most widely accepted cause for motion sickness. However, Reason[33] disregards this theory noting that signals from the inner ear and eye encoded differently and that cue conflict theory fails to explain why drivers are immune to motion sickness but their passengers are not.

There are multiple models for locomotion in VR, Bownman's taxonomy, while broad in categorization and generalized for all modes of transport, serves as a stepping stone to a more exhaustive and complete taxonomy designed by Arns. Arns taxonomy is still widely applicable and the distinction between rotation and translation allows for multiple locomotion techniques to be used when designing locomotion for a VR application. However, because Arns taxonomy does not take into account the giant leap VR technology has made over the past decade, Boletsis' typology is more applicable to current generation VR locomotion design as it considers modern VR technology and all the optimisations said technologies have implemented to make various forms of locomotion possible. However, Boletsis' typology is not without its limitations. Boletsis' typology does not take into account that VR applications can implement multiple locomotion techniques and the method Boletsis used for categorizing various locomotion techniques is up for debate with Boletsis saying that the boolean logic used to categorize each technique may have limited his final results.

The four types of locomotion that Boletsis suggests deserve further inspection. Table 5 tabulates Boletsis' typology and categorizes each type of locomotion in terms of: their ability to induce presence, the likelihood of a given type to induce simulator sickness, the spatial requirements of locomotion techniques within that locomotion type and the associated cost of implementing locomotion techniques within that locomotion type. Each entry is evaluated as either Low, Moderate or High.

Controller-based techniques are the most common implementations of locomotion in commercial VR applications. They have low spatial requirements as locomotion in the virtual world is dictated by the controllers. They require no additional hardware as modern VR products package HMDs and controllers together. This means that using a controller-based technique ensures that a VR application is widely accessible. Controller-based techniques do not inhibit presence[36] but do cause vection as the user remains

Techniques	Presence	Simulator Sickness	Space	Cost
Motion-based	High	Low	Moderate	High
Room scale-based	High	Low	High	Moderate
Controller-based	Moderate	Moderate	Low	Low
Teleportation-based	Low	High	Low	Low

Table 1: Boletsis' typology[4] tabulated in terms of the four locomotion types, their ability to induce presence, their likelihood of inducing simulator sickness, their space requirements and their associated cost.

Problem	Solutions
Inconsistent/Low frame rate	Decrease graphical fidelity
Postural instability	Ensure objects behave in accordance with their real-life counterparts
Sensory overload	Reduce number of objects or Use independent visual background
Uncanny valley	Decrease object realism

Table 2: A list of problems that occur when designing a virtual environment and their proposed solutions.

stationary throughout the duration of a session. This means that a user is more likely to experience simulator sickness[24] when a controller-based technique is used.

Unlike controller-based techniques, motion-based techniques cost more. This is because motion-based techniques generally require additional hardware (treadmill, stepper, etc.) and need more space to house said hardware. Fortunately, the added cost and spatial requirements of motion-based techniques reduces simulator sickness and greatly increases presence[39, 40].

Room scale-based locomotion techniques provide a middle ground. These techniques are cheaper than motion-based techniques, because the do not require additional hardware, and improves presence and reduces simulator sickness[44]. This is due to the one-to-one mapping of locomotion in the real and virtual world. Unfortunately, room scale-based techniques have high spatial requirements as users need to move about the room to move around in the virtual world. Room scale-based techniques limit environment design by requiring larger environments to be subdivided into interactive blocks. To overcome this teleportation-based techniques are often used as a method of transporting from one block to another. The inclusion of teleportation-based techniques introduces all of its limitations. These techniques are often unnatural and increases the likelihood of experiencing simulator sickness [27].

While it is clear that haptic feedback increases presence[35], the use of haptic feedback in reducing simulator sickness has not been well researched and provides an interesting opportunity for further investigation. One proposed method is to tether a user to a sensor that measures the tension of the tether and once a tension threshold has been passed, the player moves in the virutal environment. This method can be extended to support omnidirectional travel by utilizing additional sensors and tethers.

This review examined various environment design decisions that can reduce or induce simulator sickness. Table 2 summarizes the problems that can occur when designing a virtual environment and their proposed solutions.

7 CONCLUSIONS

In this review we looked at our current understanding of simulator sickness as it relates to locomotion in virtual reality. The underlying physiological cause of motion sickness, and by extension simulator sickness, is still not known but cue conflict theory and to a lessor extend long term memory conflicts are the most widely accepted theories. The relationship between environment design in virtual reality and simulator sickness is highlighted. The most important factor in this relationship being constant and high framerates to reduce the likelihood of experiencing simulator sickness. Objects within the environment should behave realistically or intuitively to prevent postural instability from occurring. They should also be limited in number to prevent sensory overload.

This review looked at two models for locomotion: Arns'[2] extension to Bowman's taxonomy[6] and Boletsis' typology[4], Arns' taxonomy, while exhuastive, does not take into account the leap VR technology has made in the past decade. Boletsis' model does take this into account and is reviewed extensively. The locomotion types identified by Boletsis are also reviewed with controller-based and room-scale based techniques providing the 'biggest bang for your buck'. Room scale-based techniques offer the most presence and least likelihood of inducing simulator sickness at the cost of large spatial requirements. These techniques often require an additional type of locomotion to travel beyond the bounds of the room thus introducing the pros and cons of the included technique. Controller-based techniques, due to the absence of additional hardware requirements, allow designers to ensure that their application are widely accessible. However, controller based techniques induce varying amounts of vection which, as a result, can induce simulator sickness.

The use of haptic feeback devices to reduce simulator sickness is not well researched and provides a unique opportunity for further investigation.

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