Review on simulator sickness in virtual reality and reducing it

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ABSTRACT

Simulator sickness is a major problem in the field of virtual reality. Given the ever growing popularity and accessibility of VR, it is imperative that this problem is addressed. In this review we look at how one reduces simulator sickness in virtual reality. We take a look at three key aspects - the cause of simulator sickness, measuring simulator sickness in experiments, and the current best methods for reducing it. We find that the cause of simulator sickness is best explained by the sensory conflict theory which argues that simulator sickness, like motion sickness, is due to conflicting sensory information the brain receives. The Simulator Sickness Questionnaire is identified as a key questionnaire for any VR experiment, while the benefits of measuring presence with the Presence and Immersive Tendencies Questionnaire are also discussed. We also look at some of the current design guidelines in VR centered around reducing simulator sickness, most of which focus on reducing vection and emphasise on providing an efficient form of locomotion.

CCS CONCEPTS

• **Computing methodologies** → **Virtual reality**; • **Hardware** → *Haptic devices.*

KEYWORDS

simulator sickness, virtual reality

1 INTRODUCTION

Virtual reality (VR) has recently spiked in popularity and accessibility, and major part in this is the hardware revival (such as the introduction of consumer grade VR headsets like the Oculus Rift and HTC Vive) which has greatly enhanced the user experience [5]. However, an ever present problem in VR is simulator sickness. Simulator sickness is a form of motion sickness experienced in simulators and VR. Symptoms of simulator sickness, similar to that of motion sickness but less severe, include: nausea, headache, blurred vision, and eye-strain [22, 25]. The key factor that differentiates motion sickness from simulator sickness is that simulator sickness is experienced without any physical motion unlike motion sickness.

As VR became more prominent, the term cybersickness gained popularity as a way to separate simulator sickness from the symptoms experienced with a VR headset. In 1997 Stanney et al. [35] describe the difference between the two noting that the symptoms a user experiences with cybersickness, although mostly the same as simulator sickness, are up to three times worse and advocate for the use of the different terms. However in their literature review on cybersickness, Rebenitsch and Owen [33] noted that as time went on the two terms have been used interchangeably in most literature and they have become ambiguous. Due to this ambiguity and the vast similarities between the two, in this paper we shall use the term simulator sickness.

Given the unpleasant feelings one experiences during simulator sickness, it is imperative to mitigate and manage it in virtual reality applications. Thus the purpose of this paper is to give an overview of our current understanding of simulator sickness and how to reduce it. Section 2 introduces the causes of simulator sickness, while section 3 covers what is necessary to measure simulator sickness in experiments, and how to effectively design such experiments, and section 4 goes over the current best methods of reducing simulator sickness. Finally we discuss how our proposed solution to reducing simulator sickness by using a tether to provide haptic feedback, and a stepper machine for locomotion, fits into current literature.

2 CAUSES AND TRIGGERS OF SIMULATOR SICKNESS

The physiological causes of simulator sickness or motion sickness are unclear, however there are numerous theories as to why it occurs, such as the sensory mismatch theory or the toxin detector theory. These causes are discussed below as well as the different triggers which lead to the symptoms experienced during simulator sickness.

2.1 Sensory Conflicts

Sensory conflicts, or the sensory mismatch theory, is the most commonly accepted theory for the explanation of motion sickness [3]. The underlying theory is that motion sickness occurs due to a mismatch in the sensory information the brain receives. There are three sensory systems which provide different information to the brain: the vestibular (balance), visual, and somatosensory (touch) systems.

The two main components of the vestibular system are the semicircular canals and the otolith organs. The former responds to angular acceleration, while the latter responds to linear acceleration. The somatosensory system reports the position of the head relative to the body, as well as joint movements. The visual system provides information about the motion of the subject, or the environment (it cannot however distinguish between the two [3]). When the subject is experiencing normal motion, these three systems are in harmony with one another. Figure 1 shows how they interact with each other to help produce the perception of motion. Motion sickness occurs when there is conflict between these systems.

Koch et al. [25] provide a succinct summary of the six types of sensory conflict that lead to any form of motion sickness. Two important types describe classical motion sickness and simulator sickness. Classical motion sickness, like sea sickness, arises when both the vestibular and visual systems provide information to the brain but they disagree. Simulator sickness occurs when the visual system provides information to the brain but the vestibular does not, i.e. vection. This is common in simulators and virtual reality devices so it is no surprise that this type of conflict leads to simulator sickness.

2.2 Poisoning

Another interesting hypothesis for the cause of motion sickness is the "toxin detector" hypothesis. Originally proposed by Triesman in 1977 [36], it postulates that when a person experiences motion sickness, it is their natural emetic response - the removal of toxic substances from the body. It occurs because the brain evolved to identify uncommon occurrences of visual and spatial patterns.

Golding in 2006 [13], advocates strongly for this hypothesis. He notes that the hypothesis is consistent with the fact that motion sickness is evolutionary consistent within the animal kingdom, people who are more susceptible to motion sickness are more susceptible to toxins and vomiting, and that the theory has been experimentally tested showing evidence of reduced vomiting when given toxins after the vestibular system has been removed.

However, in his 2012 paper, Oman [29] discredits this theory by explaining that vestibular symptoms should be mentioned in poisoning literature, but they are not. Also drugs that are known to be effective in combating nausea and emetic responses are ineffective against motion sickness and that Triesmans' theory remains unverified.

2.3 Postural Instability

Riccio and Stoffregen [34] put forth the postural instability theory in 1991 and argue that motion sickness is the result of the an animal failing to maintain postural stability. They postulate that one of the main goals of any animal is to maintain postural stability as this is fundamental to performing any other action. When an animal is in an environment in which is has not learned to control its postural stability, motion sickness will occur and will get more severe as time goes on. They reject the sensory conflict theory though do acknowledge that sensory stimulation plays a role in motion sickness. Bertolini and Straumann [3] argue that although this theory has solid foundation it fails to explain simulator sickness experienced by individuals who are in situations where active postural stabilization is required (e.g. sitting down).

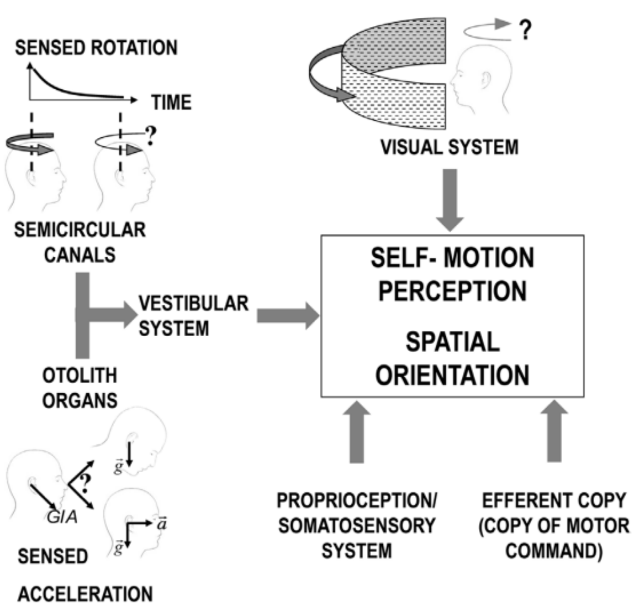

Figure 1: How the three sensory systems produce the perception of self-motion. Taken from Bertolini and Straumann [3].

2.4 Triggers

The various triggers that contribute towards simulator sickness can be grouped into three factors - technical, application design, and individual. These factors have been summarised in Table 1.

Table 1: The various triggers of simulator sickness grouped into three factors.

Technical	Application Design	Individual
Latency	Vection	Experience
Field of View	Frame Rate	Gender
IOD	Sitting vs. Standing	Age

2.4.1 *Technical Factors.*

Technical factors describe the limitations of the hardware. These factors can be solved, or at least minimized, as technology progresses.

Input latency is the major technical factor that induces simulator sickness. Due to the distortion between the users input and what is rendered on screen, it creates a sensory conflict and leads to simulator sickness symptoms [17].

An increase in the field of view (FOV) is highly linked with simulator sickness, though at the same time it is also linked with an increase in presence (presence is discussed in section 3) [33].

Another technical factor is the distance between the headsets' lenses known as the Inter-Optical Distance (IOD). Howarth [15] describes the phenomenon known as Accommodation reflex, or Accommodation-Convergence conflict, which can occur if there is continual conflict between the IOD and the inter-pupilary distance. The accommodation reflex is the eyes' reflex when changes in focal distance occur. This can lead to eye-strain, visual fatigue, heterophoria (when the resting position of the eyes are not parallel to each other) and more.

2.4.2 *Application Design Factors.*

Application design factors differ from technical factors in that even if the perfect hardware was being used, certain aspects of a VR application will still affect the user.

A prominent factor is vection. Vection is the illusion of self-motion and is highly linked with simulator sickness. It occurs when motion is detected in either the linear or rotational axes of the human body. The sensory conflict theory, as described above, is the most common explanation for the occurrence of vection [14].

Frame rate is a significant contributor to the latency experienced by a user. Increasing complexity in an application will lower the frame rate. The consistency of the frame rate is also important. A constantly changing frame rate is more likely to induce simulator sickness than a steady, low frame rate [17].

Whether a user is standing or sitting when using a VR application is another factor. Mehri et al. [28] found that simulator sickness was more common in user who stood as opposed to sitting. This also supports the postural instability theory.

2.4.3 Individual Factors. Individual factors are the characteristics of a user which increase the likelihood of simulator sickness occurring. Perhaps the biggest characteristic is the amount of experience one has with VR. The more experienced a user is with VR, the less likely they are to get simulator sickness [17]. Females are more likely to get simulator sickness than males [13], children and elders are more susceptible than adults [8, 32], and individuals with a history of migraines are likely to experience more intense simulator sickness [11].

3 EXPERIMENT DESIGN FOR SIMULATOR SICKNESS

Given the impact simulator sickness has on a virtual reality experience, it is not surprising that a great amount of research has gone into understanding and mitigating it.

This section will look into the most common ways in which simulator sickness experiments are run and what methods they use to measure simulator sickness.

3.1 The Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) was developed by Kennedy et al. [21] to quantify simulator sickness. It covers 16 symptoms divided into three categories: nausea, oculomotor, and disorientation. Nausea describes symptoms like stomach pain and burping, oculomotor tracks symptoms related to the vision system like eyestrain and blurred vision, and disorientation covers dizziness, vertigo and other orientation related symptoms. Using the questionnaire, the subject will rate the severity for each of the 16 symptoms, which is then used to calculate a sub-score for category. Finally, using the sub-scores and a predetermined weight, a total simulator sickness score is calculated.

Initially based off the Pensacola Motion Sickness Questionnaire (MSQ) [18], the SSQ was configured to better suit the measurement of simulator sickness as opposed to the MSQ, since the SSQ took into account the discrepancies between motion sickness and simulator sickness.

Kennedy's et. al paper on the SSQ [21] is a highly cited paper in virtual reality literature, and any experiment which attempts measure simulator sickness should use the SSQ both before and after the experiment.

3.2 The Virtual Reality Sickness Questionnaire

In 2018 the Virtual Reality Sickness Questionnaire (VRSQ) [23] was developed in an attempt to modernize the SSQ. They postulate that the SSQ was developed for the use of simulators as opposed to virtual reality headsets - simulators provide inertia whereas VR headsets do not. Through the use of factor analysis they reduced the number of questions in the questionnaire down to nine questions with each categorized into oculomotor or disorientation. The nausea category was removed.

Although they highly recommend the use of the VRSQ over the SSQ, there are limitations to the VRSQ that the SSQ does not suffer from. Firstly the study only had twenty-four participants - the minimum number of people required to generalize the factor analysis results. The SSQ was developed with the use of factor analysis on over 1000 use cases [21].

Secondly the study contains an insufficient explanation for the removal of the nausea component. Even though results pertaining to nausea were mixed, it does not necessarily mean that the component should be removed. It was recommended that further study be put into the VRSQ, particularly to find a more substantial reason for removing the nausea component.

3.3 The Presence Questionnaire and Immersive Tendency Questionnaire

Another concept to measure in VR experiments is presence. Presence is the feeling of being located in one environment even if the subject is physically located elsewhere. To measure this the Presence Questionnaire (PQ) and Immersive Tendency Questionnaire (ITQ) was developed by Witmer and Singer [37]. More specifically, the ITQ was developed to measure the varying tendencies of subjects to undergo presence, whilst the PQ is used to measure presence itself. Both questionnaires use a seven-point scale, and they depend solely on self-reported information.

Although presence is a subjective experience, Witmer and Singer identified that the strength of presence one experiences depends on both the individual and the virtual environment. Thus they were able to deduce four factors which contribute to the experience of presence, namely: Control, Sensory, Distraction and Realism factors. A substantial portion of the PQ was derived from these factors.

Although presence is an entirely different concept from simulator sickness, presence can be a compounding factor. In the same paper regarding the PQ/ITQ, Witmer and Singer [37] found that subjects who report higher levels of simulator sickness also report lower levels of presence than those who report low levels of simulator sickness. This is unsurprising, given that any feelings of nausea detract from the experience of the virtual environment. Given this correlation, and the importance of creating an immersive experience for the user, presence is an important concept to measure.

3.4 Other Measurements

Apart from measuring simulator sickness, there are other interesting measurements to make. One is to use postural instability tests both before and during the use of VR. These tests make use of a tandem Romberg stance, where the subject stands heel-to-toe, evenly distributing weight between their legs, arms folded across their chest, and facing forwards [10]. Prothero and Parker [31] used this test to measure postural instability by counting the number of times the subject breaks this stance.

Physiological measurements provide an objective measurement when testing for simulator sickness. These measurements should be made before the test as a control, and throughout the duration of the test. Kim et al. [24] measured 16 different physiological variables on 61 participants. They found a significant correlation between simulator sickness scores and an increased heart rate, the eye blinking rate, respiration rate, respiratory sinus arrhythmia (changes in heart rate along with breathing), and heart period (time between heart beats).

4 MITIGATION AND MANAGEMENT OF SIMULATOR SICKNESS

As expected, there is no silver bullet for avoiding or alleviating simulator sickness given that simulator sickness is polygenic and polysymptomatic (meaning that it has multiple causes and affects people differently) [20]. However there are some well-researched methods and promising leads for mitigating or managing the simulator sickness problem, which are discussed below.

4.1 Design Guidelines

There are some general guidelines one can follow to manage simulator sickness. These focus on minimizing the triggers of simulator sickness. In Table 2 we summarise a set of guidelines to follow to reduce simulator sickness.

Table 2: A set of guidelines to follow to avoid simulator sickness.

What to do	What to avoid
Use repeated short exposures	Using for longer than 2 hours
Increase the FOV	Long lengths of acceleration
Have a high frame rate	Random camera movements

In 1987, Kennedy et al. published some general guidelines for alleviating simulator sickness in military flight simulators [19]. They found that people who have had little exposure to simulators are the most prone to simulator sickness, and that repeated exposure is a potent way to mitigate simulator sickness. Other interesting findings include: simulations should not last longer than two hours, one should make frequent use of timeouts, and one should not use the simulator if they are not in their normal state of fitness (hungover, sleep loss, or existing stomach pain). Although these findings were based on flight simulators they can be applied to general VR use.

More recently, Porcino et al. published a set of design guidelines for minimizing cyber sickness in VR headsets [30]. They mention a set of factors to take into consideration:

- Length of acceleration - long lengths of acceleration increase discomfort.
- Random camera movements - camera movements not made by the user increase discomfort.
- Length of time using the device - longer use times increase discomfort.
- Field of view - increasing FOV decreases discomfort but also reduces immersion.

They also put forth a design guideline for reducing discomfort due to "infinity focus", which is when all objects in a scene appear in focus. This guideline allows the creation of a dynamic focus model, which takes into account blur level, refocus time, observer's attention, depth, and persistence.

4.2 Travel in Virtual Reality

Since vection is a significant contributor to simulator sickness, it stands to reason that developing an efficient form of travel in a virtual environment is key to reducing simulator sickness. There are a variety of techniques of locomotion. Boletsis [5] proposes a typology to describe the four types of locomotion, reproduced in figure 2. Below we cover one example from each type of locomotion:

4.2.1 Real-walking. In this technique users physically walk within some confined space and this motion is translated into movement within the virtual environment. Their movement can either be tracked using the headset's position or via the limb movements of the user. The major limiting factor of this technique is the physical size of the room in relation to the virtual environment's size. Solutions to this problem include: algorithmically directing the user so that they do not move out of the tracked area (also known as redirected walking) or making the tracked area the same size or bigger than the virtual environment [5, 6].

Matsumoto et al. [26] proposed an application of redirecting walking in which users walk along an "unlimited corridor". The user walks along a convex shaped wall, touching it as they go, but within the virtual environment they are walking along an infinite corridor.

4.2.2 Walking-in-place. This is a technique in which the user travels within the virtual environment by performing step-like actions on the same spot. Although walking-in-place cannot match real-walking in terms of intuitiveness, it has been described as the closest thing to real walking [12]. It also has the benefits of being cost effective and convenient.

Most applications of walking-in-place are done via a treadmill but there are some other interesting applications - most notably a stepping machine [5]. It is not extensively researched but is affordable (compared to the treadmill) and provides proprioceptive feedback. An interesting implementation of the stepping machine by Bozgeyikli et al. [6] used an optical tracker and reflective markers to track the motion of the machine. This movement was transferred into the virtual environment. For direction they used the users head movement, but also rotated the machine if the users head turned by more than 45 degrees. They found that the stepper machine provided a similar experience compared to traditional walking-in-place methods but did not provide more comfort and some users reported that it required a lot of physical effort.

Matthies et al. [27] designed an inexpensive and simple stepper machine that makes use of a generic sports stepper, Arduino, and a potentiometer. When the user steps on the stepper, it turns the potentiometer which transmits its value, and the user moves forward in the virtual environment. However they did not use a VR headset as pretests found that users kept falling off the stepper, so they used a CAVE design which is a room surrounded by displays. Although users reported better immersion when using the VR stepper, they could not find statistical significance in their results.

4.2.3 Teleportation. In this form of locomotion, the user points to where they want to go and they are instantly transported there. This can be done via a controller or a gesture. Although the motion is not continuous, breaking immersion, it does not induce simulator sickness as the user does not experience any vection. A disadvantage of teleportation is that it can be disorientating. Attempts have been made to mitigate this - in 2018 Bhandari et al. [4] attempted to reduce disorientation by using a technique called Dash, whereby the user is quickly and continuously moved. This constant motion allows the user to retain some optical flow cues which helps reduce disorientation. Their study found that participants experienced less disorientation and similar levels of simulator sickness when compared to normal teleportation. [5–7].

4.2.4 Controller based. Controller based techniques are very common in VR applications. They make use of typical controllers like joysticks or touchpads and are low cost, have a simple implementation and are familiar to users [5]. In their 2016 study of Locomotion techniques for users with Autism Spectrum Disorder [6], Bozgeyikli et al. found that users responded well to joystick-based controls. It had low levels of simulator sickness, though lower levels of presence. However, overall, it ranked the highest in terms of preference.

4.3 Haptic Feedback

Haptic feedback provides a sense of touch that is expected when touching virtual objects. It is an important aspect in providing an immersive experience and increased presence [2]. Not much research has been done on the impact haptic feedback has in reducing simulator sickness, though a PhD. dissertation by Insko [16] in 2001 found that passive haptics did not have a significant effect on simulator sickness scores.

Another interesting use of haptic feedback is the application of wearable devices used to simulate the feeling of touching objects. Choi et al. [9] developed Wolverine, a low cost haptic feedback device that helps simulate the grasping of rigid objects, however it's stiffness cannot be dynamically changed. Haptic feedback has also been used to assist neurosurgeon residents train for aneurysm clipping with VR with mostly positive reports [1].

5 DISCUSSION

The three main competing hypotheses for the cause of simulator sickness are the sensory conflict theory, the toxin detector hypothesis, and the postural instability theory. The sensory conflict theory describes the cause of simulator sickness as an imbalance in the sensory information the brain receives, the toxin detector hypothesis postulates that motion sickness is a natural emetic response, while the postural instability theory argues that motion sickness is the result of failed postural control.

All three theories are stemmed in well-cited literature, however the toxin detector hypothesis has the greatest deal of challenge against it and is not used in practice. The postural instability theory is gaining traction in recent studies and has the advantage of being able to be tested objectively with a postural stability test. The sensory conflict theory is mentioned in a great deal of recent studies and literature surveys [3, 25], adding to its validity. Although it's the most accepted theory, it fails to predict the intensity of the symptoms. One thing is clear though, we still do not fundamentally understand why simulator sickness occurs.

What we can do is limit the factors that increase the likelihood of simulator sickness occurring. A great deal of triggers have been identified in various literature, but the most important are summarised in table 1. Perhaps the easiest way to prevent or reduce simulator sickness is to limit the technical triggers. These triggers are only relevant due to the limitations of our current hardware. As the inevitable progress of hardware continues these triggers, like latency, will become increasingly irrelevant.

Good application design is also key to limiting the triggers of simulator sickness. Reducing the amount of vection experienced in the application, having high frame rates, and making use of current design guidelines can help reduce simulator sickness.

Individual triggers make up the bulk of the triggers, and in his textbook Jerald describes the individual as the greatest factor for VR sickness [17]. Some individual triggers, like experience, can be mitigated but some are inherent characteristics and nothing can be done about them.

When designing an experiment around simulator sickness, or virtual reality for that matter, the SSQ [21] should be used to measure simulator sickness. Presence is also an interesting component to measure, as it is a compounding factor to simulator sickness. Should one decide to measure presence, the PQ and ITQ should be used [37]. Both the SSQ and PQ/ITQ originate from highly cited papers and appear in most literature. The SSQ should be taken before and after the user performs the test, while the ITQ should be taken before and the PQ should be taken after.

Recently an attempt to modernize the SSQ was made [23] by creating a Virtual Reality Sickness Questionnaire, however due to the low number of participants in the study compared to the SSQ, the insufficient explanantion for the removal of the nausea category, and the ubiquity of the SSQ in VR experiments, it is not recommended to use the VRSQ.

Two other measurements are postural instability tests and physiological measurements. Both provide an objective measurement compared to the subjective nature of questionnaires. However there is little research covering the use of these measurements in VR experiments and thus the full extent of their validity is not known. In any case, should one decide to use these measurements, they should be used in conjunction with the SSQ, and the PQ/ITQ should presence also be of interest.

The need for reducing simulator sickness is clear, but how one approaches such a challenge is no simple feat. Understanding what causes simulator sickness, how one should go about measuring and designing experiments around it, and what the latest studies and best practices to avoid it are is an important first step.

Current literature on how to reduce simulator varies, but it is clear that suppressing the various triggers is a must. Since vection is a major trigger for simulator sickness, most research has looked into different types of locomotion in virtual reality with the key areas being real-walking, walking-in-place, teleportation, and controller based methods.

Real-walking provides the most immersive experience and the least simulator sickness, however it is difficult and expensive to implement, and would not work in a large virtual world. Controller-based methods are common, familiar to users and have fairly low

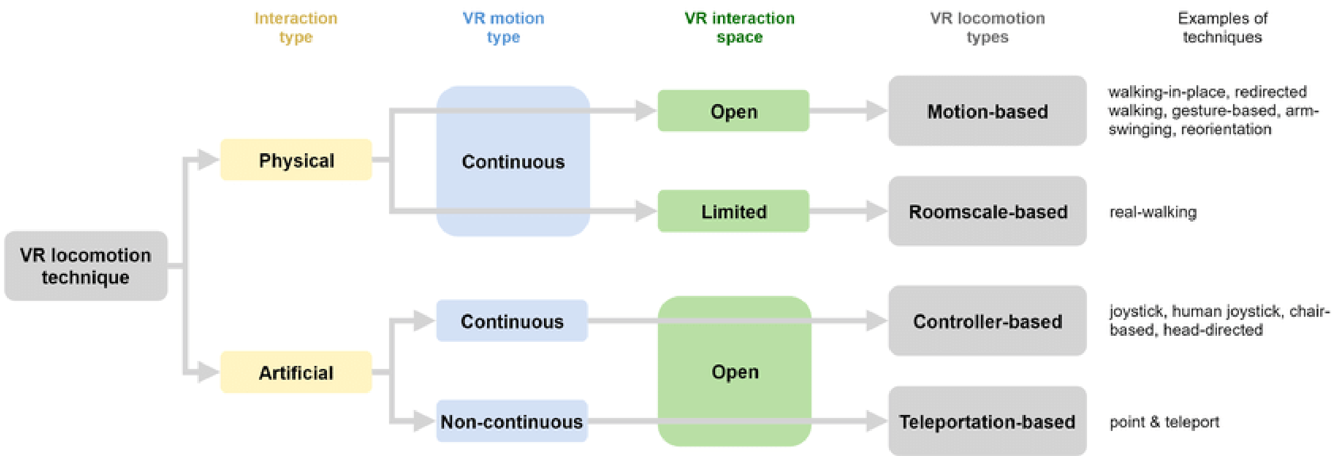

Figure 2: Boletsis' [5] locomotion typology.

levels of simulator sickness, however they provide the least immersion. Walking-in-place seems to be the next best thing compared to real-walking being cheaper and convenient. Most applications use a treadmill device which is cumbersome and expensive, and research into cheaper alternatives, like a stepping machine, are sparse and a proposed solution which includes a stepper machine will certainly add to this field of knowledge. Teleportation almost completely avoids vection, given its instant acceleration, however it breaks immersion and can be disorientating. It also would not work for certain types of games like racing simulators [5–7, 12].

Haptic feedback is also an interesting area of research but there is a severe lack of research on its effect on simulator sickness. What is clear though is that it improves immersion within the virtual environment [2].

Our proposed solution to reducing simulator sickness in VR includes the use of a tether device attached to a user which provides haptic feedback as they move forward, which will contribute to this sparse field of virtual reality research.

6 CONCLUSIONS

In this review we looked at the current literature on how one goes about reducing simulator sickness in virtual reality. We focused on three main areas: what causes simulator sickness, how virtual reality and simulator sickness experiments are designed, and what current literature says about reducing simulator sickness.

The cause of simulator sickness is not clear though the prevailing theory is that is a consequence of sensory conflicts. The main trigger for simulator sickness, which also ties in to the sensory conflict theory, is vection. Reducing vection is key to reducing simulator sickness. Other theories regarding simulator sickness include the toxin detector theory, which has its issues, and the postural instability theory.

In designing an experiment around simulator sickness, using the simulator sickness questionnaire is highly recommended. Presence is also an interesting concept to measure, and should one decide to measure it the presence and immersive tendency questionnaire should be used. These should be used both before and after a subject performs the test. Attempts to modernize the simulator sickness questionnaire have been made but there are problems with validity regarding these. Postural instability tests and physiological measurements are alternate measurements one could make which provide an objective measurement, but the use of these in experiments is sparse.

When designing a VR application or experiment, current guidelines are a good place to start when trying to reduce simulator sickness. These guidelines include simple yet effective rules that can reduce simulator sickness a great deal, like length of time in the simulator, acceleration duration, field of view and more. How one performs locomotion within the virtual environment also plays a key role in reducing simulator sickness.

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