Motion Sickness Reduction for 6-DoF-Navigation in a Virtual Solar System

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Declaration of Authorship

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2. Where I have quoted from the work of others, the source is always given. Except for such quotations, this thesis is entirely my own work.
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1 Introduction

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2 Background and Related Work

While Virtual Reality technology has gained more and more traction over the recent years, 30% to 80% of users encounter some form of sickness symptoms during their exposure to virtual environments [1]. Additionally, these sickness symptoms can have lasting effects after the exposure as well [2]. The high number of affected users has led to cybersickness being one of, if not the biggest roadblock to a more widespread adoption of Virtual Reality Devices.

According to LaViola [2] the symptoms of exposure to virtual environments include:

- Eye strain
- Headache
- Pallor
- Sweating
- Dryness of mouth
- Fullness of stomach
- Disorientation
- Vertigo
- Nausea
- Vomiting.

Vertigo, in the case of VR-sickness particularly benign paroxysmal positional vertigo (BPPV), is a condition where the individual experiences a false sense of motion, or spinning, and objects or surroundings appear to swirl or move [3].
Several studies also found that severity of symptoms increases with longer exposure times to virtual environments [4, 5, 6]. However, some studies show that users can adapt, and overall sickness reduces with repeated exposure [7].

Throughout the study of these symptoms, several terms have been used to compound these sickness symptoms that appear to be similar to the symptoms of motion sickness. Initially, the term Simulator Sickness was used to describe motion sickness encountered during exposure to flight simulators [8]. The term originated from the assessment of military flight simulators [9]. While Simulator Sickness is still used in recent publications, the terms Cybersickness or VR Sickness are generally used to differentiate, and closer examine the side effects of virtual environments from simulator sickness [8, 10]. The term VR Sickness specifically is used in discussions and studies about sickness symptoms involving head-mounted displays (HMD) [11, 12]. This terminology is often used interchangeably across literature. The terms Cybersickness and VR Sickness will be used in this study, as Stanney, Kennedy, and Drexler [13] argue that, while sickness from virtual environments shares many of the symptoms also experienced during simulator sickness or motion sickness, the sickness profiles are different.

	Simulator sickness	Sea sickness	Space sickness	Cybersickness
Highest rating	Oculomotor	Nauseagenic	Nauseagenic	Disorientation
Middle rating	Nauseagenic	Oculomotor	Disorientation	Nauseagenic
Lowest rating	Disorientation	Disorientation	Oculomotor	Oculomotor

Table 2.1: Related conditions symptom profiles according to Rebenitsch and Owen [1].

According to Rebenitsch and Owen [1] cybersickness and other sickness symptoms similar to motion sickness are polysymptomatic (many symptoms) and polygenic (different manifestation for individuals) and therefore complex to understand and describe. To make the sickness and its symptoms easier to survey and examine, Kennedy et al. [9] categorize the symptoms listed above into three categories:

- Nauseagenic symptoms (dryness of mouth, fullness of stomach, nausea, etc.)
- Oculomotor sypmtoms (eye strain, headache, etc.)
- Disorientation symptoms (vertigo, dizziness, etc.)

The main arguments for the distinction between simulator sickness and cybersickness are that during cybersickness, disorientation symptoms rank highest and oculomotor symptoms rank lowest, while simulator sickness and traditional motion sickness usually have the inverted profile, where disorientation symptoms rank lowest [13].

Cybersickness can also occur without stimulation to the vestibular system, purely through visual cues, unlike motion and simulator sickness, where stimulation of the vestibular system is needed, but not visual stimulation [2]. Additionally, Stanney et al. [13] determined that cybersickness can be up to three times more severe than simulator sickness. Saredakis et al. [8] also note significantly higher average Simulator Sickness Questionnaire scores, although both mention, the scores and questionnaire were established with a focus on military flight simulators used by military personnel. While recently, the Simulator Sickness Questionnaire has been adopted to measure cybersickness in virtual environments, which might be the reason for the higher average scores [8].

2.1 Common causes of cybersickness

Over the recent years there have been several theories trying to explain the sickness symptoms experienced during extended exposure to virtual environments, especially since the commercialisation of head-mounded virtual reality devices. The most common Theories are the sensory conflict theory and the postural instability theory. Additionally, there are some theories that try to explain why sickness symptoms occur in virtual environments like the rest frame theory, and the vergence accommodation conflict theory.

2.1.1 Sensory conflict theory

The generally most accepted, and widespread theory is based on a sensory mismatch either between sensory systems of the body, or between sensory input and expectation given the perceived environment. Most commonly, a sensory conflict due to vection (the illusion of self movement while stationary) is argued to be the main cause of cybersickness [14, 15]. Although, other studies like Palmisano, Mursic, and Kim [16] suggest, that vection is neither the sole, nor primary source of sensory conflict. Sensory conflicts like vection can also occur outside virtual environments, for example when a person is in a stationary vehicle while an adjacent vehicle begins to move [2].

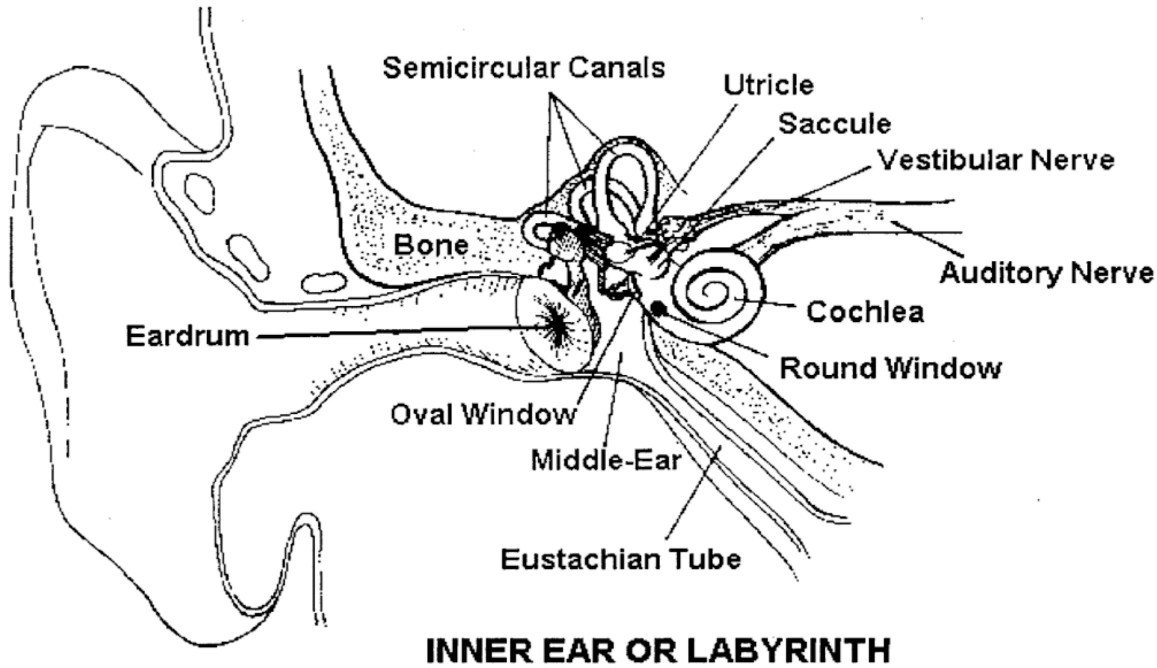

Figure 2.1: The components of the vestibular system [2].

Important for the sensory conflict theory are visual perception and the vestibular system, shown in Figure 2.1. The vestibular system consist of the Semicircular Canals to sense angular momentum, and the Utricle and Saccule to sense linear momentum. Together, the system functions to compensate for movement, stabilize vision, maintain head posture, and maintain balance [17]. In virtual environments, the sensory mismatch is usually between the visual system receiving optical flow patterns characteristic of self motion, while the vestibular system does not perceive these changes in motion. This sensory conflict lies at the root of simulator sickness and was identified early on, when Barrett and Thornton [18] noticed that subjects showed simulator sickness symptoms caused by conflict between the visual presentation of motion and the lack of corresponding vestibular sensation in their fixed-base simulators. Barrett and Thornton also noticed, that subjects only showed sickness symptoms when the simulator was in a perspective similar to driving a car, but showed no symptoms when viewing the car from outside, similar to driving a remote controlled car, as well as passengers showing more severe symptoms than drivers, indicating that involvement in motion is a factor in the occurrence of simulator sickness [19, 18].

The sensory conflict theory is the most popular theory to explain cybersickness, because it has a steadily growing amount of studies supporting it, and the theory is intuitive to understand [1, 19]. However, the theory has been criticised by several studies, because sensory conflict theory only states that sickness is preceded by a sensory conflict, but is unable to predict when cybersickness will occur, or how severe sickness symptoms will be [2, 1, 20].

2.1.2 Postural instability theory

Another theory for cybersickness symptoms is the postural instability theory proposed by Riccio and Stoffregen [21]. They found that motion sickness is preceded by periods of postural instability, where small uncontrolled movements and changes in the subjects centre of gravity occur, and the subject's ability to maintain postural stability is hindered [21, 22]. Stoffregen and Smart [23] translated the theory into three predictions:

- Experiences of motion sickness are always preceded by increases in postural instability.
- Experiences of motion sickness persist until postural stability is restored.
- People who are more naturally unstable are more likely to become motion sick during provocative simulation.

These predictions have been solidified and are supported by numerous studies on visually induced motion sickness [22]. Chardonnet, Mirzaei, and Merienne [24], as well as other studies propose to use the changes in range, variance, and frequency of the subject's centre of gravity as a measurement of postural sway. Based on the accessibility of devices to measure individual's centre of gravity, those measurements have found increasing popularity in studies to objectively measure subject's postural stability and indicate the potential onset of cybersickness symptoms [25]. A comparison between the

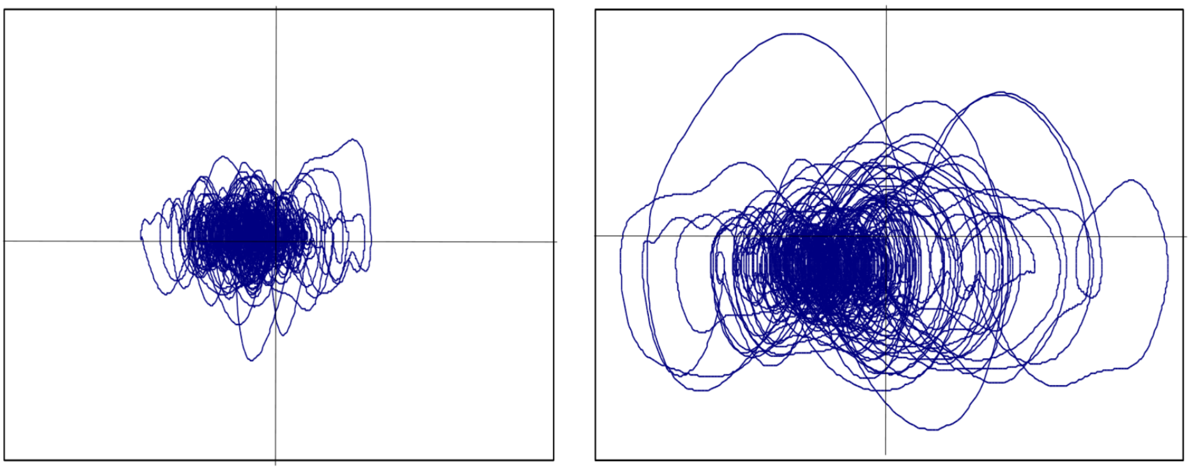

Figure 2.2: Comparison of phase portraits (position (in cm) vs. velocity (in cm/s)) for well (left) and sick (right) subjects in a dataset measuring postural stability [26].

natural postural sway of a subject compared to the postural sway when experiencing motion sickness is shown in Figure 2.2. The recent study by Lim et al. [25] successfully used postural stability measurements to train an algorithm to predict VR content's potential to induce cybersickness, as shown in Figure 2.3, based on the postural instability theory.

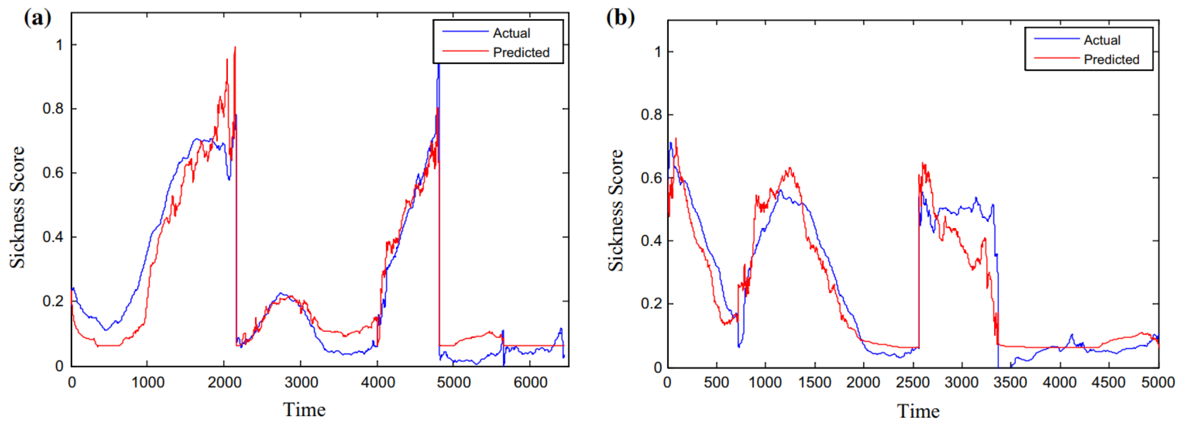

Figure 2.3: Actual sickness (blue) and predicted sickness (red) of (a) training and (b) testing set produced by the prediction algorithm by Lim et al. [25].

2.1.3 Other theories

Rest frame theory

Similar to sensory conflict theory, the rest frame theory argues that a mismatch in sensed gravitation and perceived up-direction is the cause for sickness symptoms [1]. The rest frame theory also shows

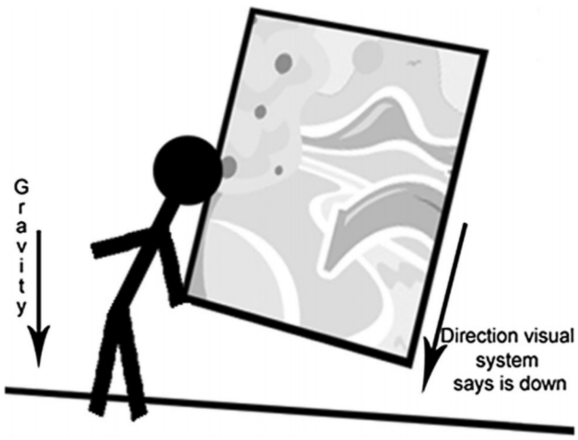

Figure 2.4: Example of sensory mismatch according to rest frame theory [1].

similarities to the postural instability theory, as the discrepancy between perceived up-direction and gravity leads to postural instability and following sickness symptoms [1]. An example of this sensory mismatch, and resulting postural instability is shown in Figure 2.4. The theory also supports the postural instability theory in situations where postural control is lessened, such as in seated positions where the individual's posture is stabilized. Several studies like Chang et al. [27], and Duh, Parker, and Furness [28] found, that superimposing some form of static frame of reference into the virtual environment significantly improves postural stability and reduces cybersickness symptoms.

Vergence-accommodation conflict theory

Another theory to explain cybersickness symptoms, especially oculomotor symptoms, is the vergence-accommodation conflict theory. Vergence is the simultaneous lateral movement of the eyes

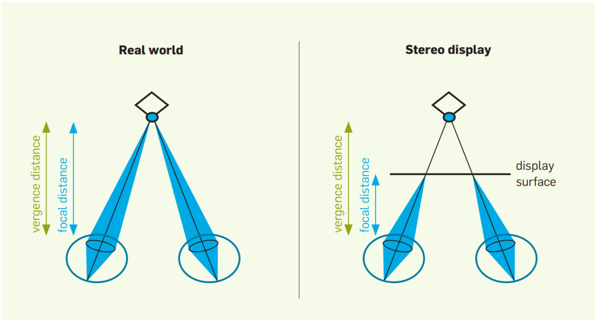

Figure 2.5: Difference between vergence and accomodation distance in the real world (left) and stereoscopic displays (right) [29].

when an individual's visual system is adjusting to objects at different distances [30]. Accommodation is the process of adjusting both eye's focal lengths, focusing on the perceived object [1]. In virtual environments, especially in head-mounted displays, images are presented at a fixed screen depth. This leads to conflict with real life expectations, as vergence and accommodation do not occur naturally at different distances like in stereoscopic displays [8], as shown in Figure 2.5. Kim, Kane, and Banks [30] noted that content with high levels of stimulation usually contain more changes in stimulus distance, and therefore variance of stimulus distance, and level of visual stimulation both increase visual discomfort and eye strain.

2.2 Methods of measurement

Due to the polysymptomatic and polygenic nature of cybersickness, measurements of cybersickness can prove difficult, as there is a variety of mostly internal, nonobservable, and subjective symptoms [10]. Additionally, there can be large individual differences in symptom profiles and susceptibilty, and most symptoms develop over time and can occur even after the exposure to virtual environments [10]. Historically, the use of questionnaires is the most popular method of recording occurrences of cybersickness [1, 8]. The most widely used questionnaire is the Simulator Sickness Questionnaire (SSQ), developed by Kennedy, Lane, Berbaum, and Lilienthal [9]. Recently, several studies have tried refining the SSQ to adapt it for the assessment of virtual reality and head-mounted displays, resulting in the Virtual Reality Symptom Questionnaire (VRSQ) by Ames, Wolffsohn, and McBrien [31], and the CyberSickness Questionnaire (CSQ) by Stone III [32]. In addition to the extensive post-session questionnaires, single item questionnaires like the Fast Motion Sickness Scale (FMS) by Keshavarz and Hecht [33] that are polled in regular intervals during the virtual environment exposure have gained popularity in cybersickness studies. Because of the subjective nature of questionnaires, these methods of quantifying cybersickness symptoms have been criticised and several methods of objective measurement have been researched. Kim et al. [34] studied the changes in sixteen different electrophysiological signals and found several measurements with a significant positive or negative correlation. However, these measurements require special equipment that may be unavailable or unintuitive, leading to a low adoption rate among studies related to cybersickness symptoms and detection. A more easily accessible method of objective measurement has been measuring the postural stability of individuals exposed to virtual environments and use the changes in the centre of gravity (CoG) as an indicator for cybersickness symptoms [25].

2.2.1 Questionnaires

Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire developed by Kennedy, Lane, Berbaum, and Lilienthal [9] is, despite being developed in 1993, still one of the most popular methods to measure cybersickness symptoms [8]. Kennedy et al. [9] based their developments on the Pensacola Motion Sickness Questionnaire (MSQ), where they identified several deficiencies that could be improved:

- to provide a more valid index of overall simulator sickness severity as distinguished from motion sickness;
- to provide subscale scores that are more diagnostic of the locus of simulator sickness in a particular simulator for which overall severity was shown to be a problem;
- to provide a scoring approach to make monitoring and cumulative tracking relatively straightforward.

As part of the last objective, they sought to eliminate the configural approach of the MSQ allowing to automate the administation and scoring of results [9]. Additionally, the studies involving the MSQ used differences between post- and pre-exposure scores as their main indicator, and a pre-exposure checklist where subjects are asked whether they were in other than their "usual state of fitness" [9]. Kennedy et al. [9] removed both, the two-step approach, and the pre-exposure checklist in an effort to streamline the administration and scoring process, noting that the SSQ is "intended only for application to post-exposure symptoms, with the further precondition that a screening of "unhealthy" subjects is required [before exposure]" [9, p. 207]. To tailor the questionnaire to better fit simulator exposure and its sickness symptoms, Kennedy et al . [9] eliminated symptoms that might give misleading indication, were selected too infrequently, or showed no change in frequency or severity. Additionally, they sorted the remaining symptoms into separate clusters labeled "Oculomotor" (SSQ-O), "Disorientation" (SSQ-D), and "Nausea" (SSQ-N) [9]. The distinction allowed to apply a subscale to each cluster, reflecting the impact of simulator exposure on a different "target system" in the subject [9]. It also simplified the process of determining where and in what way a simulator may cause problematic symptoms [9].

	Weight		
SSQ Symptom	*N*	*O*	*D*
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total	[1]	[2]	[3]
Score			
N = [1] $\times$ 9.54			
O = [2] $\times$ 7.58			
D = [3] $\times$ 13.92			
TS = [1] + [2] + [3] $\times$ 3.74			

Table 2.2: SSQ Symptoms and Scoring according to Kennedy et al. [9].

Table 2.2 shows the remaining symptoms and their clustering, as well as the method of scoring the SSQ as derived by Kennedy et al. [9]. The SSQ symptoms are rated on a four-point scale from 0 to 3, then multiplied by either 1 or 0 (omitted in the table) according to the weight section of table 2.2, and finally summed up in each column [9]. The total and subscale scores are then calculated using the formulas in the "Score" section of table 2.2 [9]. Kennedy et al. [9] also mention the possibility to further refine the questionnaire by:

- splitting the "Oculomotor" cluster into the disturbance of visual processing (blurred vision, difficulty focusing) and the symptoms caused by the disturbance (headache, eyestrain);
- splitting the "Nausea" cluster into premonitory signs (increased salivation, burping) and advanced stages of nausea (nausea, sweating);

As well as moving some symptoms into a "tired and hungry" cluster, believed to be an artifact created by the time spent during the exposure [9]. However, Kennedy et al. [9] state that there are not enough simulator-relevant symptoms to provide adequate reliability for smaller clusters, and recommend using the three cluster solution. Despite the general adoption of the SSQ, there are several problems, especially for the assessment of cybersickness symptoms in virtual environments, that Kennedy et al. [9] recognize in their study.

			SSQ	Scale M	
Simulator	**Aircraft**	*N*	*O*	*D*	*TS**
2F64C	SH-3	14.7	20.0	12.4	18.8
2F120	CH-53E	7.5	10.5	7.4	10.0
2F121	CH-53D	7.2	7.2	4.0	7.5
2F110	E-2C	7.1	13.1	6.8	10.3
2E7	F/A-18	6.1	5.1	6.2	6.8
2F117	CH-46E	5.4	7.8	4.5	7.0
2F87F	P-3C	4.5	15.2	4.3	10.5
2F132	F/A-18	2.7	6.1	0.6	4.2
2F112	F-14	1.7	1.8	0.0	1.5
M		7.7	10.6	6.4	9.8
SD		15.0	15.0	15.0	15.0

* Total Severity

Table 2.3: SSQ Scale Means by Simulator for the Calibration Sample according to Kennedy et al . [9].

The weights for the scoring functions are derived from 1119 pairs of MSQs collected from 9 simulator sites shown in table 2.3 as a calibration sample [9]. Therefore, the modal position on the Symptoms or the intermediate sums is no indication for symptomatology with respect to simulator sickness across simulators in general, as the zero point contains between 40% and 75% of the observations in the calibration dataset [9]. This also means, the sensitivity is at the upper extremes of the symptomatology range, and the scores should be compared to the calibration set, in table 2.3, instead of interpreted on their own [9]. Kennedy et al. [9] conclude that the results should not be used to distinguish among simulators without problems, but identify and discriminate problem simulators from those without problems [9]. Other, more recent studies, like Sevinc and Berkman [35], and Rebenitsch and Owen [1], criticise the usage of the Simulator Sickness Questionnaire because of its complex structure, and development process, as it involves only a sample of highly trained professionals, and a small amount of simulator experiments, which both do not comply with the modern day HMD-based virtual environments, and diverse applications and users [35].

Virtual Reality Symptom Questionnaire

Recent studies like Ames, Wolffsohn, and McBrien [31] tried to develop a questionnaire based on the MSQ and SSQ specifically for the assessment of cybersickness symptoms. Ames et al. [31] note that existing methods like the SSQ do not properly address the ocular symptoms that contribute to cybersickness symptoms in virtual environments. Examining existing virtual reality research, they identified 23 symptoms split into two clusters, 12 non-ocular, and 11 ocular symptoms [31]. Ames et al. [31] also decided to expand the symptom response scale to seven options sorted into four labels: "none" (0), "slight" (1, 2), "moderate" (3, 4), and "severe" (5, 6). In the development study, Ames et al. [31] exposed 16 subjects to a stereoscopic video played on a head-mounted display, and recorded the occurring symptoms with the developed VRSQ in two-minute intervals immediately after the exposure for a total of six post-exposure examinations. From the results, they identified 13 symptoms with high item-total correlations, that remain in the final questionnaire [31]. While, the "nausea" symptom did not meet the correlation criteria, it was retained for research that might involve more "dynamic imagery" [31]. However, similar studies, like Stone III [32], criticise the validity of the VRSQ to evaluate cybersickness, as Ames et al. [31] only used video input on a head-mounded display, without any user interaction or input method, resulting in visual stimulus only, similar to existing studies on visually induced motion sickness, but not explicitly virtual reality sickness symptoms [32]. Additionally, Stone III [32] notes concerns about the validity of the psychometric evaluation and the small sample size used in the development study. Davis, Nesbitt, and Nalivaiko [36] also note the lack of published studies using the VRSQ as a method to evaluate cybersickness symptoms in their review on cybersickness literature, while Rebenitsch et al . [1] do not mention the VRSQ at all.

CyberSickness Questionnaire

In his study criticising the VRSQ and SSQ, Stone III [32] also proposes an alternative solution to measure cybersickness symptoms, the CyberSickness Questionnaire (CSQ). Similar to the method Kennedy et al. [9] used to refine the SSQ from the MSQ, they reinterpreted the results of the SSQ in a cybersickness context. For this, Stone III [32] selected the symptoms clearly indicating cybersickness:

- headache
- eyestrain
- nausea
- blurred vision
- dizzy (eyes open)
- dizzy (eyes closed)
- vertigo
- difficulty focusing
- fullness of head

Additionally, they decided to amalgamate "Severe" and "Moderate" responses from the SSQ [32]. Stone III [32] found a two factor solution by separating the Symptoms into two clusters: "Dizziness" and "Difficulty focusing". Stone III [32] also notes that the SSQ can still be used to record post-exposure symptoms, while the scoring can be done using the developed CSQ approach by following these steps:

1. Administer the SSQ after the exposure to virtual environments.
2. Remove the unneccesary symptom items from the collected data.
3. Combine "Moderate" and "Severe" options for each symptom item, resulting in responses "None" (0), "Slight" (1), and "Moderate" (2).

4. Compute the CSQ factors, similar to the SSQ, by multiplying each symptom item with the weight shown in table 2.4 and adding up the items to form the final scores.

	Dizziness	**Difficulty focusing**
Headache	.50	.
Eyestrain	.	.58
Difficulty focusing	.	.89
Nausea	.84	.
Fullness of head	.	.55
Blurred vision	.	.81
Dizziness (eyes open)	.89	.
Dizziness (eyes closed)	.99	.
Vertigo	.54	.

Table 2.4: CSQ nine-item, two-factor model for scoring, according to Stone III [32]

Stone III [32] notes that preliminary evidence, and the comparison of CSQ scores with other established visually-induced motion sickness scoring methods support the validity of the resulting CyberSickness Questionnaire. However, they note based on the CSQ scores of their study, 57% of the 202 participants reported no dizziness and 40% reported no difficulty focusing, which implies cybersickness was very low, and the study was not focused explicitly on inducing cybersickness symptoms [32]. The review of questionnaires by Sevinc et al. [35] has tested and approved the validity of the CSQ and concludes that it is a more accurate method of measuring cybersickness symptoms than the SSQ, as it was developed with a lager sample size and specifically based on the use of virtual reality applications to induce sickness symptoms.

3 Current State/Problems of CosmoScout

3.1 CosmoScout Concepts

3.1.1 SPICE Coordinate Systems

3.2 Problems with free movement

3.3 Problems with automatic movement

4 Implemented Solutions

4.1 Floor Grid

4.2 FoV Vignette

One of the most common methods to reduce cybersickness risks and symptoms is decreasing the Field of View [37] [38]. To alleviate cybersickness during movement with high detail, and movement in the peripheral areas of vision, a vignette is implemented to limit the Field of View, focusing the users attention and preventing the influence of activity in the peripheral vision from adding to cybersickness symptoms. The Vignette is mainly planned for movement close to an object's surface, where peripheral detail is significantly higher compared to movement in interplanetary space. The vignette is implemented as a post-processing shader, drawing a 2D effect over the rendered scene based on an inner and outer radius, which are both adjustable in the settings. The inner radius determines the maximum distance from the center of the viewport, where a clear field of view is guaranteed. While the outer radius determines the minimum distance from the center, after which the screen is fully opaque and set to a custom color. The area between the inner and outer radius consists of a gradient, blending between fully transparent, showing the rendered scene, and the custom color the gradient meets at the outer radius. Since the vignette is supposed to block peripheral details distracting the user during movement, the vignette is only drawn during movement, and disabled when standing still or during sporadic movement. This allows reducing the risk of cybersickness symptoms during critical phases, while still maintaining the feeling of presence as much as possible, as reducing the field of view negatively influences the feeling of presence [38]. An adjustable threshold for the velocity is used, since slow movements tend to only produce low risks of cybersickness symptoms. Additionally, an adjustable deadzone is implemented, allowing for a grace period where the vignette is not displayed when passing the threshold to avoid flickering on short, quick movements, or velocities close to the threshold, that pass the threshold when fluctuating slightly. After passing the velocity threshold for at least the deadzone time or longer, the vignette is eased in or out by a fade animation with an adjustable duration, to make the transition to the limited field of view more comfortable and less noticeable.

4.3 Automatic Movement Overhaul

5 User Study

6 Further Work

A Appendix

This is the appendix. You can put all the stuff you like here.

A.1 Appendix Sections

The enumeration for the appendix is different.

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