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

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Master Thesis

Hochschule Hannover
Faculty IV – Business and Computer Science
Course of Studies M. Sc. Applied Computer Sciences

March 25, 2021

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Declaration of Authorship

I hereby declare that this thesis, and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

1. Where I have consulted the published work of others, this is always clearly attributed.

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.

3. I have acknowledged all main sources of help.

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Contents

1 Introduction

1.1 Virtual Reality

1.2 CosmoScout VR

1.3 Scope of the project

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].
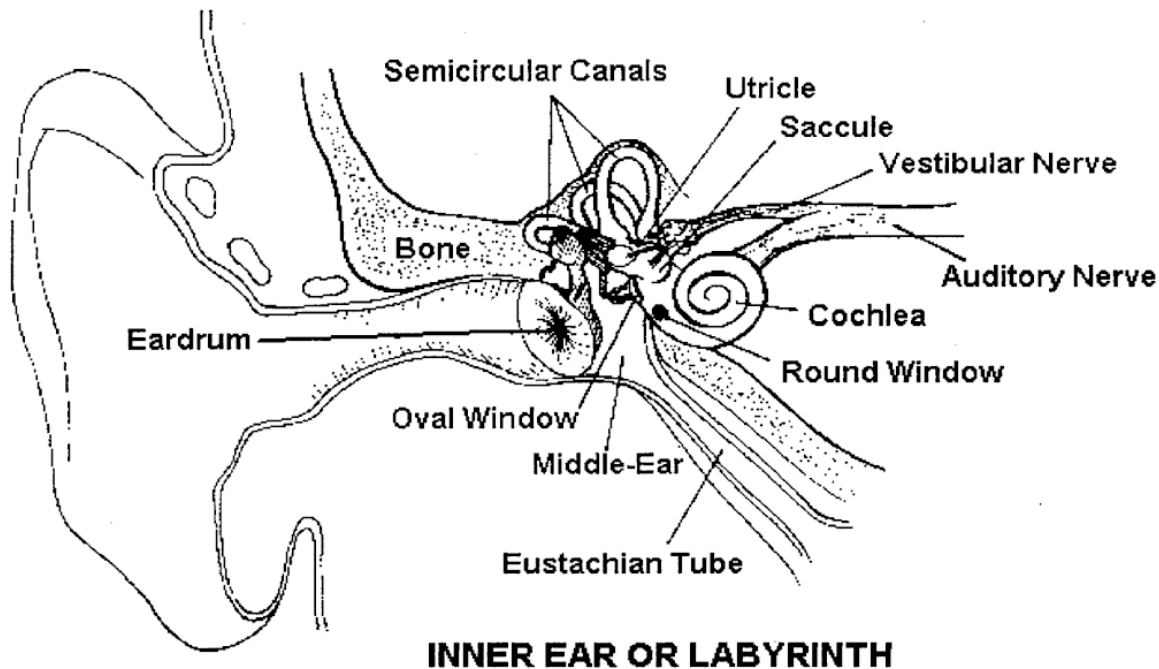

Figure 2.1: The components of the vestibular system [2].

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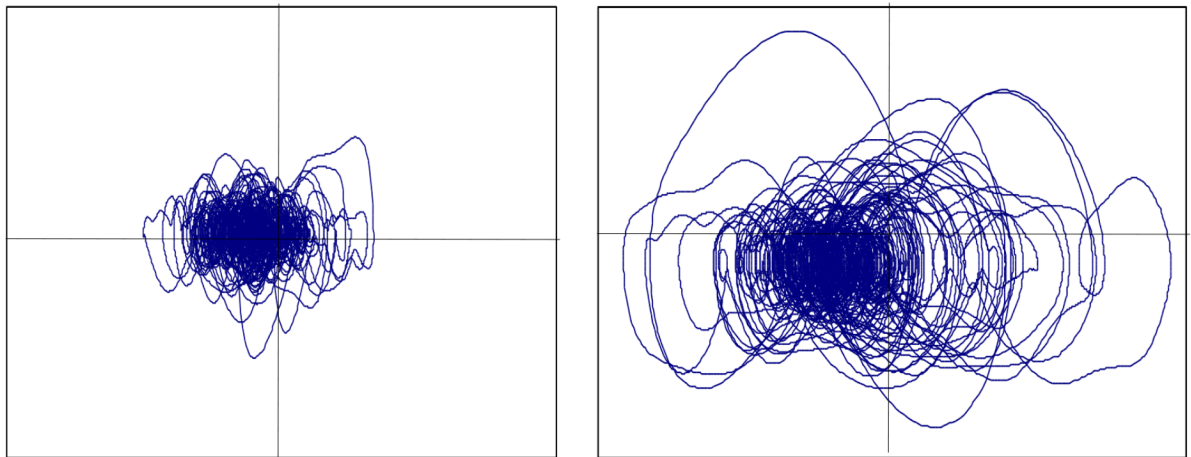
Figure 2.2: Comparison of phase portraits (position (in cm) vs. velocity (in cm/s)) for well (left) and sick (right) subjects in a dataset measuring postural stability [26].

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.

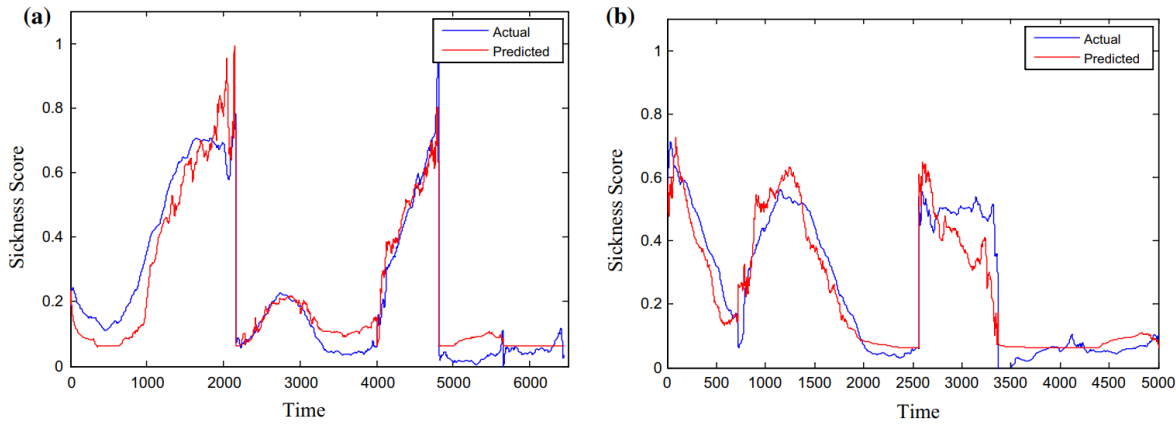Figure 2.3: Actual sickness (blue) and predicted sickness (red) of (a) training and (b) testing set produced by the prediction algorithm by Lim et al. [25].

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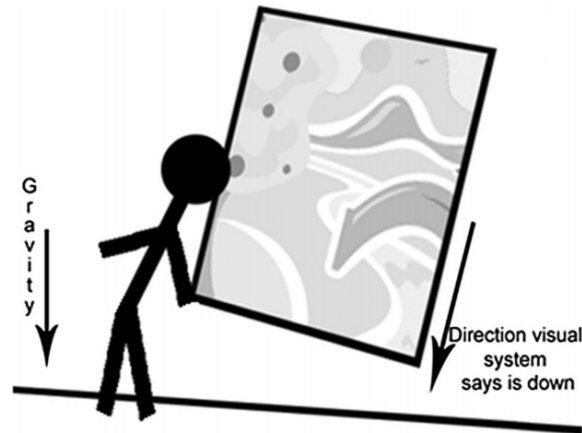
Figure 2.4: Example of sensory mismatch according to rest frame theory [1].

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
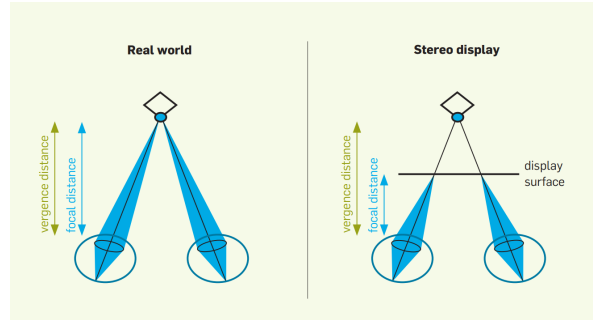

Figure 2.5: Difference between vergence and accomodation distance in the real world (left) and stereoscopic displays (right) [29].

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]. Another popular questionnaire is the broader formulated Motion Sickness Assessment Questionnaire (MSAQ) by Gianaros, Muth, Mordkoff, Levine, and Stern [33], designed to assess visually-induced motion sickness symptoms regardless of stimulus context. In addition to the extensive post-session questionnaires, single item questionnaires like the Fast Motion Sickness Scale (FMS) by Keshavarz and Hecht [34] 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. [35] 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 cyber-sickness 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 Subjective Measurements

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. 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 administration and scoring of results. 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". Kennedy et al. 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. 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). The distinction allowed to apply a subscale to each cluster, reflecting the impact of simulator exposure on a different "target system" in the subject. It also simplified the process of determining where and in what way a simulator may cause problematic symptoms.

SSQ Symptom	Weight		
	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. 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. The total and subscale scores are then calculated using the formulas in the "Score" section of table 2.2. Kennedy et al. 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. However, Kennedy et al. 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. recognize in their study.

| Simulator | Aircraft | N | SSQ Scale M | | |
			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. 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. 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. conclude that the results should not be used to distinguish among simulators without problems, but identify and discriminate problem simulators from those without problems. Other, more recent studies, like Sevinc and Berkman [36], 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 [36].

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. note that existing methods like the SSQ do not properly address the ocular symptoms that contribute to cyber-sickness symptoms in virtual environments. Examining existing virtual reality research, they identified 23 symptoms split into two clusters, 12 non-ocular, and 11 ocular symptoms. Ames et al. 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, they 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. While, the "nausea" symptom did not meet the correlation criteria, it was retained for research that might involve more "dynamic imagery". However, similar studies, like Stone III [32], criticise the validity of the VRSQ to evaluate cybersickness, as Ames et al. only used video input on a head-mounted 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. Additionally, Stone III notes concerns about the validity of the psychometric evaluation, and the small sample size used in the development study. Davis, Nesbitt, and Nalivaiko [37] 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 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. Stone III found a two factor solution by separating the Symptoms into two clusters: "Dizziness" and "Difficulty focusing". They also note 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 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. The review of questionnaires by Sevinc et al. [36] 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.

Motion Sickness Assessment Questionnaire

Gianaros, Muth, Mordkoff, Levine, and Stern [33] developed the Motion Sickness Assessment Questionnaire (MSAQ) with the goal to assess motion sickness across a broad range of contexts. Similar to other studies developing questionnaires, Gianaros et al. recognized the multi-dimensionality of motion sickness symptoms. However, they felt sopite-related symptoms, like drowsiness, yawning, and disengagement from the environment, were underrepresented in existing questionnaires [33, 38]. Including sopite-related symptoms, Gianaros et al. identified four dimensions of motion sickness:

- gastrointernal symptoms, like sickness, queasiness, or nausea;

- central symptoms, like dizziness, disorientation, lightheadedness, or blurred vision;

- peripheral symptoms, like being sweaty, clammy, or hot, or cold sweat;

- sopite symptoms, like being annoyed, tired, fatigued, or uneasy.

Similar to the SSQ, they designed the MSAQ to be used both, for overall motion sickness scores, and assessment of distinct dimensions via subscale scores.

Symptom Item	Gastrointestinal	Central	Peripheral	Sopite
I felt sick to my stomach	.36	.	.	.
I felt faint-like	.	.45	.	.
I felt annoyed/irritated	.	.	.	.36
I felt sweaty	.	.	.27	.
I felt queasy	.36	.	.	.
I felt lightheaded	.	.45	.	.
I felt drowsy	.	.	.	.36
I felt clammy/cold sweat	.	.	.27	.
I felt disoriented	.	.45	.	.
I felt tired/fatigued	.	.	.	.36
I felt nauseated	.36	.	.	.
I felt hot/warm	.	.	.27	.
I felt dizzy	.	.45	.	.
I felt like I was spinning	.	.45	.	.
I felt as if I may vomit	.36	.	.	.
I felt uneasy	.	.	.	.36

Table 2.5: Symptom items and subscale groups, according to Gianaros et al. [33]

The Questionnaire consists of between 16 and 20 symptom questions, with the original 16 questions shown in table 2.5 [33, 36]. Each symptom question is rated on a nine-point scale from 1 (Not at all) to 9 (Severly). The subscale scores are the sum of the weighted symptom items, multiplied by the weights in the respective columns, and the total motion sickness score is obtained by the following formula, according to Gianaros et al.:

- Overall Motion Sickness Score = (sum of all symptom items (without weights)) $\times$ 1.44

While, Gianaros et al. note that the generated symptoms during their study may stem from a relatively narrow range of motion sickness contexts, they offer the possibility to modify the questionnaire to more accurately reflect the multiple dimensions of motion sickness across different motion environments. Although the development process of the questionnaire was based on visually-induced motion sickness using optokinetic drums and not virtual reality environments, Sevinc et al. [36] note in their review on cybersickness that the Motion Sickness Assessment Questionnaire was used in several virtual reality and simulator studies in the recent years. Lastly, Gianaros et al. argue that their questionnaire supplies valid descriptors of motion sickness in and for general population, since the symptom items were generated independently by non-experts during the early phases of their study.

Fast Motion Sickness Scale

In contrast to the multi-dimensional questionnaires, Keshavarz and Hecht [34] proposed and validated a single-item questionnaire that can be administered during stimulus presentation. This allows for simple and continuous gathering of motion sickness data during the presentation. The FMS consists of a verbal rating every minute on a 20-point scale between 0 (no sickness) and 20 (frank sickness), and primarily measures the two cardinal symptoms in motion sickness: nausea, and general discomfort [34]. Keshavarz and Hecht explain, they use a 20-point scale to better differentiate among lower degrees of

motion sickness symptoms and capture different states of both well-being and sickness. They argue the extended scale also helps participants to express their feelings and experience more precisely. Conversely, Keshavarz and Hecht also note the questionnaire's indifference to the physiological correllates or root causes of motion sickness, and participants are unable to differentiate between nausea and other precursor symptoms in their answers. In their defense, they argue the Fast Motion Sickness Scale is only designed to quantify the subjective impressions of nausea and general discomfort related to motion sickness, without addressing the underlying symptoms or causes. Their validation study showed high
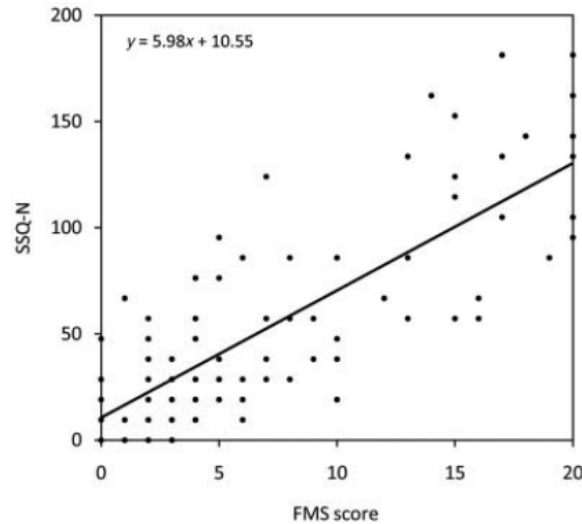

Figure 2.6: Scatter plot showing the distribution of peak FMS score and SSQ-N subscore for all participants of the study by Keshavarz and Hecht [34].

correlation between the peak scores of the FMS and the Nausea subscale score of the Simulator Sickness questionnaire (SSQ-N), as shown in figure 2.6. Additionally, Rebenitsch and Owen [1] conclude that one-item rating scales are acceptable to monitor motion sickness symptoms, even though they are not as sensitive or thorough as the multi-dimensional, longer Questionnaires. Sevinc and Berkman [36] also mention a rise in single-item assessment methods, but note that the FMS is the only version that has been psychometrically evaluated.

2.2.2 Objective Measurements

In contrast to the subjective measurements that have been employed in most studies on cybersickness, several studies have tried linking physiological measurements to the occurrence of cybersickness symptoms in individuals. Finding reliable physiological cybersickness indicators potentially allows monitoring symptoms without interrupting the virtual reality exposure through frequent polling of the subject, as used in the FMS, while still generating a continuous measurement stream to examine symptom development and causes over the duration of the virtual environment exposure [1]. One of the broadest studies regarding objective measurements of cybersickness symptoms is the study by Kim et al. [35], where they collected and tested 16 electrophysiological signals that were used in other studies as measurements of sickness symptoms in order to find significant correlations indicating a reliable, objective method measuring cybersickness. The signals collected before, during, and after the exposure

included the following items, which showed a significant correlation to reported sickness in previous studies:

- heart period

- respiratory sinus arrhythmia

- respiration rate

- eyeblink rate

- fingertip pulse volume

- fingertip temperature

- skin conductance

- gastric tachyarrhythmia (arrhythmic disruptions of the gastric musculature, often resulting in an upset stomach or uneasy feeling)

- electroencephalogram (EEG) power spectrum

Kim et al. used a quite provocative stimulus to test the physiological signals, as 45 out of the 57 subjects experienced cybersickness symptom during the 9.5 minutes of exposure to virtual environments and subjects reported cybersickness an average of five times during the exposure. They also employed a 33-item pre-immersion, and a 49-item post immersion questionnaire to link to better link their electrophysiological findings to the self-reported levels of cybersickness symptoms experienced. The questionnaires were compilations of different popular cyber- and motion sickness and susceptibility questionnaires including the Simulator Sickness Questionnaire. Kim et al. found significant correlations, especially between SSQ scores and gastric tachyarrhythmia, eyeblink rate, respiration rate, respiration sinus arrhythmia, and heart period. They found, gastric tachyarrhythmia, skin conductance, respiratory sinus arrhythmia, and relative delta power at F3 and T3 electrode locations of the EEG were significantly higher than the previous recorded baseline. They also found, heart period, fingertip skin temperature, fingertip pulse volume maximum amplitude, and relative beta power at F3 and T3 electrode locations were significantly decreased compared to the recorded baseline. Kim et al. suggest that due to the correlation between gastric tachyarrhythmia and cybersickness, the autonomic nervous system may play a bigger part in the occurrence of cybersickness than previously assumed. Similar to this study, Roberts and Gallimore [39] found electrogastrogram (EGG) measurements, to detect gastric tachyarrhythmia, to be a strong indicator of virtual reality exposure and cybersickness symptoms. Other studies have also used electrocardiogram (ECG) and blood pressure measurements to indicate cybersickness, as they found the heart beat becomes stronger, and the blood flow shows lower turbulence during exposure to virtual environments [40, 41].

Davis et al. [37] note that one detractor to widespread use of physiological measurements may be the costly hardware and difficulty to analyse the results. A middle ground has been presented in several studies using measurements of postural stability as an objective, low cost, and continuous indicator of cybersickness symptoms [1]. However, Rebenitsch et al. [1] also note that postural sway measurements in many studies are not as continuous or without the disturbance of the subject as they are often presented, since most measurements require the subject to enter a specific stance for the measurement. Most

studies use the amplitude, magnitude, and frequency of postural sway to distinguish and predict motion sickness symptoms, while older studies also examine the time till failure (time until a stance cannot be maintained) or the stance breaks (number how often the subject fails to maintain a stance) during a specific timeframe [1]. Villard, Flanagan, Albanese, and Stoffregen [42] and Dong, Stoffregen, and Yoshida [43, 44] both noticed in their studies that subjects who did not experience significant sickness symptoms had an increased standard deviation of motion during their exposure period, while subjects that experienced sickness symptoms showed greater variability with smaller average motion compared to the baseline. Some other studies mentioned similar findings and suggest that subjects may self-adapt to virtual reality exposure by consciously avoiding head movements when experiencing sickness symptoms [1]. Another method of low cost, objective measurement of cybersickness is presented by Chardonnet et al. [24], who found consistent results measuring a subject's centre of gravity (CoG) with a high correlation to measured SSQ scores. Lim, Lee, Won, Kala, and Lee [25] further extended this measurement, as they proposed to use the VR devices inertial measurement unit (IMU) to record head dispersion during the exposure period. They introduced Head Dispersion as a measurement of stability from the following Eq. 2.1

$$ Head\ Dispersion = \sqrt{\frac{\sum(roll - \overline{roll})^2 + \sum(pitch - \overline{pitch})^2}{n}} \tag{2.1} $$

With the *roll* and *pitch* values in degree, and $\overline{roll}$ and $\overline{pitch}$ as the mean values along the session. To validate their approach Lim et al. compared their IMU sensor data to the centre of gravity sway area measured by an external sensor as proposed by Chardonnet et al. and found high correlation between their measured Head Dispersion and CoG sway area. The major advantages of this method are the lack of additional measuring devices needed, and the synchronization processing, while delivering a continuous indicator of potential sickness symptoms. However, due to the study's recency, it has not yet seen further adoption or larger sample size studies.

2.3 Methods of Mitigation

Despite the lack of a definitive cause or widespread adoption of objective measurements to monitor cybersickness symptoms, several mitigation techniques and best practices have proven effective and have found widespread adpotion as early as 1992, when McCauley and Sharkey [10] formulated their best practices and recommendations to prevent and mitigate cybersickness and simulator sickness symptoms:

Exposure time should be limited until adaption to the VE has occurred, as some studies found that users adapt to virtual environments with repeated exposure [7].

Tasks that require high rates of linear or rotational acceleration should be avoided, or kept brief, until the individual has fully adapted to the altered environment, as virtual reality content with high interaction and visual stimulation tends to lead to more severe experiences of motion sickness [8].

Users of VEs should be considered on an individual basis when determining an adaptation program. While this recommendation is focused on adaption programs for simulators, it is also applicable to virtual reality users, as they show individual differences in cybersickness susceptibility or, for example, preferred locomotion method [22].

Self-movement through a VE should be at high altitudes above the terrain and/or at lower speeds, as high peripharal motion and visual flow are related to cybersickness occurrence and severity [45].

Additionally, *unusual and extraordinary maneuvers should be avoided in VEs*, as abrupt and counterintuitive movements can further disorient the user, increasing the risks of cybersickness.

Finally, *users of VE systems should be informed of the possible adverse effects and should be advised to allow for recovery time after cybertravel before actively engaging in potentially dangerous activities in the real world, such as driving*, since studies have shown that cybersickness symptoms can occur delayed after the exposure and have potentially lingering effects [2].

Apart from these general recommendations, several techniques have found widespread adoption and have shown a positive impact in mitigating cybersickness symptoms, like the limitation of the Field of View, or the insertion of stable frames of reference into the virtual scene.

2.3.1 Field of View Limitation

The interaction between Field of View (FoV), cybersickness, and the individual's feeling of presence, have been the subject of many studies, trying to identify the connections and possibly find an optimal solution for the FoV, where cybersickness symptoms are minimised, while maintaining the feeling of presence as much as possible [46]. Duh et al. [47] also found vection to be strongly tied to FoV, as subjects mainly seem to receive information about vection from their peripheral visual field. Therefore, a wide FoV causes a greater perception of self-motion, which tends to lead to increased postural disturbance, and generally resulting in more severe cybersickness symptoms. Studies like Fernandes and Feiner [48] recommend to dynamically or at least strategically manipulate the Field of View in order to reduce visual flow in the peripheral field during periods of high visual flow, reducing the impact of the resulting vection on cybersickness symptoms. Duh et al. examined the limits of narrow Field of Views and found that, while the experienced motion sickness increased with higher FoV, there is a significant increase at the 120°-150°interval. Additionally, participants in the study by Lim et al. [25] reported "less noticeable" black regions until the FoV dropped below 60°. Lim et al. conclude that FoV limitations should be individually adjusted, as users react differently to varying degrees of FoV limitations, as well as dynamic and fixed FoV limitation. Finally, they note that, according to their study, dynamic FoV processing and limiting can decrease VR sickness symptoms by up to 37%.

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 [47] [49]. 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 [49]. 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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