Get Well Soon! Human Factors' Influence on Cybersickness after Redirected Walking Exposure in Virtual Reality

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Abstract. Cybersickness poses a crucial threat to applications in the domain of Virtual Reality. Yet, its predictors are insufficiently explored when redirection techniques are applied. Those techniques let users explore large virtual spaces by natural walking in a smaller tracked space. This is achieved by unnoticeably manipulating the user's virtual walking trajectory. Unfortunately, this also makes the application more prone to cause Cybersickness. We conducted a user study with a semi-structured interview to get quantitative and qualitative insights into this domain. Results show that Cybersickness arises, but also eases ten minutes after the exposure. Quantitative results indicate that a tolerance towards Cybersickness might be related to self-efficacy constructs and therefore learnable or trainable, while qualitative results indicate that users' endurance of Cybersickness is dependent on symptom factors such as intensity and duration, as well as factors of usage context and motivation. The role of Cybersickness in Virtual Reality environments is discussed in terms of the applicability of redirected walking techniques.

Keywords: Virtual Reality, Cybersickness, Human Factors, Redirected Walking, Rotation Gain, Immersion

1 Introduction

Since Virtual Reality (VR) systems are becoming a commodity, new challenges occur that focus user experience in addition to technical development. Virtual Environments (VE) are of theoretically infinite size, while VR setups in homely environments are limited in the size of their trackable area. Redirected walking (RDW) techniques are used to overcome this spatial conflict, while maintaining natural walking as the best-perceived navigation metaphor [1]. Using different approaches, they manipulate the user's walking trajectory in the virtual world. Users might, for instance, perceive themselves as walking on a straight line, while in the real world they walk on a curved path. Besides their technical efficiency (i.e. degree of spatial compression), user experience aspects have to be considered when implementing RDW techniques. Symptoms of Cybersickness (e.g. nausea, disorientation, or oculomotor fatigue) pose a crucial threat to VR systems in general and are expected to be even stronger when RDW techniques are applied. Apart from Cybersickness, reduced user immersion can result due to the purposeful degradation of system fidelity [2].

To address the question of how the virtual world can be reliably mapped into real-world boundaries, while keeping immersion as high and Cybersickness as low as possible, we examine the influence of Human Factors on Cybersickness symptoms. We therefore conducted a user study in a VR environment that employs dynamic rotation gains, and measured the influence of various factors on Cybersickness levels before, right after, and 10 minutes after the VR exposure.

The remainder of this article is structured as follows: We provide an overview on Human Factors in VR, Cybersickness, and RDW techniques in section 2. Our experimental procedure is described in section 3, and the quantitative and qualitative results of the study are presented in section 4. We discuss the role of Cybersickness based on these results and outline future work in section 5. Section 6 summarizes our contribution.

2 Related Work

In this section, we present relevant related work regarding Human Factors in the context of VR applications (subsection 2.1), Cybersickness (subsection 2.2), and RDW techniques (subsection 2.3).

2.1 Human Factors in Virtual Reality

Human Factors are discussed since the early stages of VR development to attain human performance efficiency. Alongside task characteristics (e.g. the suitability of a task for a VE), Stanney et al. identified user characteristics, design constraints imposed by human sensory and motor physiology, as well as health and safety issues that have to be considered when VE systems are implemented [3]. To maximize human performance, the experienced sense of presence should be as high, and the interaction techniques as efficient as possible. Both goals can only be reached if VR hardware provides visual, auditory and haptic/kinesthetic output that convince the sensitive human sensory system of authentic input [4].

Both *presence* and *immersion* are used to describe the relation between the user's (self-)perception in the virtual world and the immediate physical surroundings. There is widespread agreement that both are desirable properties, however their exact definition and distinction is controversially discussed [5]. *Immersion* is either defined as inherent property of the display system that could be objectively quantified [6], or as a perceptual user response to the VE [7]. We adopt the latter definition as the impression of being enveloped by and interacting with a continuous stream of stimuli [7]. We refer to the inherent properties as *system immersion* [2] or *sensory fidelity*, which we define as the degree to which display and transformation of sensory information are similar to the real world [8]. *Presence*, on the other hand, is the subjective experience of being physically situated in the VE instead of the physical locale [7]. We consider system immersion a precondition for (user) immersion, which is in turn a precondition for a sense of presence. Measuring presence is most effectively done by verbal reporting [9] or with a post-questionnaire [7].

2.2 Cybersickness as Critical Factor

Besides human performance and perceptual reactions, the well-being and safety of users is of equal importance [10]. Cybersickness is considered a crucial threat to the adoption of VR technology [3], even if sickness-inducing applications might still be perceived as highly enjoyable [11]. It is mostly defined as symptoms of motion sickness, but occurring during or after VR system exposure [12]. The symptoms vary individually and have multiple influencing factors [13]. They include eye strain, headache, pallor, sweating, dryness of mouth, fullness of stomach, disorientation, vertigo, ataxia, nausea, and might even lead to vomiting [14]. With those symptoms in common, the phenomena motion sickness, simulator sickness and Cybersickness seem equal, but they are caused by slightly different situations: Motion sickness occurs mostly on moving vehicles (e.g. ships) and simulator sickness on devices that simulate motion by visual displays and moving platforms (e.g. flight simulators), while Cybersickness can be induced by visual stimuli alone [15].

A number of different theories attempt to explain the biological mechanisms that cause motion sickness. The *sensory conflict theory* suggests that a mismatch between different sensory subsystems causes the symptoms [16]. It explains factors specific to VR systems well, such as mismatches between user motion and visual display due to latency or tracking inaccuracy. While commonly employed to explain symptoms, the theory has been criticized for it's lack of predictive power [17]. The *postural instability theory* was proposed as an alternative [18]. It explains the symptoms as the body's reaction to phases of unstable posture, during which the postural control loop adapts to unknown or changing environmental conditions. While it also lacks an explanation of the biological causes and effects, in some cases it succeeds in predicting sickness levels based on length and intensity of postural instability phases [19]. Recent research indicates that the theory might be unconfirmed, though no reliable numerical evidence could be obtained [20]. The *rest frame hypothesis* is based on the notion that our perceptual apparatus optimizes the estimation of spatial relationships by assuming certain objects in the environment as stationary [21]. This reference coordinate system is called the rest frame. The theory postulates that sickness symptoms arise due to conflicting cues that indicate different parts of the environment should be considered stationary. Lastly, the *poison theory* attempts to explain why the human body reacts with nausea and vomiting. It argues that perturbations of the spatial frameworks defined by the different senses can be caused by certain types of motion but also the ingestion of toxins [22]. According to the theory, the body reacts with nausea and vomiting as a survival mechanism to remove the alleged poisonous substance.

The most widely applied instrument to quantify Cybersickness is the Simulator Sickness Questionnaire (SSQ) [15], which was originally developed to identify "problematic" flight simulators [23]. The SSQ consists of 16 symptoms that, in a series of factor analyses, were found to cluster in three subscales: nausea, oculomotor, and disorientation. The SSQ was derived from 1,119 underlying data sets of professional pilots using several flight simulators, and scaled such that every subscale and a total score that comprises all 16 symptoms have a zero point and a standard deviation of 15 [13]. Based on this calibration, motion sickness, simulator sickness, and Cybersickness show different symptom profiles: Nausea appears to be highest rated for motion sickness, oculomotor for simulators and disorientation for Cybersickness [24,25]. Furthermore, while Kennedy et al. consider an SSQ total score of 20 as indicating a bad simulator, it turns out that SSQ total scores are higher when applied to VR systems instead of flight simulators [26]. More VR-specific measures are less validated, and therefore not widely adopted, while objective measures (e.g. heart rate, blink rate, electroencephalography) are expensive to perform and rely on intrusive equipment [15].

There are several Human Factors that influence the severity of Cybersickness symptoms. Experience with the used technology is known to have a positive impact on well-being [27], in a way that tolerance towards Cybersickness is learnable, respectively trainable [28]. Furthermore, women tend to be more susceptible to Cybersickness than men. This could be caused by anatomical differences (e.g. women have larger fields of view, which leads to more flicker perception [14]), hormonal levels, or biased response behavior, since men tend to withhold information about vulnerability [29]. Another factor is age: Motion sickness appears stronger on children (2–12 years old), but in contrast to that, Cybersickness appears to be stronger on users older than 30 years. Other factors that contribute to Cybersickness are the overall health status (e.g. overweight, upset stomach, etc.) and mental rotation ability [27]. Further factors depend on task or hardware properties: Low acceleration movements, high degree of control, low time on task, appropriate blur level and low latency have a positive impact on users' well-being [30].

Based on factors that positively influence the occurrence of Cybersickness, a number of technical measures have been proposed to improve the VR system experience. These range from improvements in rendering over specialized sickness-reducing navigation techniques to guidelines for the overall design of virtual scenes. On the rendering level, an adaptive field of view during head rotations [31], dynamic blurring [32], or simulated depth-of-field rendering [30] have been proposed. Navigation methods try to minimize the amount of vection caused by passive movement through the scene [33], or mitigate its impact by providing subtle motion prediction cues [34]. Regarding general scene design it has been shown that scene complexity and realism can increase discomfort in VEs [35] and, e.g., ramps are preferable over stairs [36].

In summary, Human Factors have always been discussed to create VR hardware that provides authentic output (i.e. sensory fidelity) and system immersion. All benchmarks that are used to evaluate VR systems, such as presence, immersion, Cybersickness, and task performance—regardless of their exact definition—benefit from high system immersion, and might therefore be compromised if system immersion is limited.

2.3 Cybersickness in Redirected Walking Applications

Redirected Walking techniques spatially compress the virtual scene, to enable walking through larger virtual spaces than the physical bounds permit. Initial work on the subject demonstrated the feasibility of the method in a restricted scenario [37]. In a virtual scene, subjects walked along a series of predefined waypoints in a zigzag fashion. The turning motion at each waypoint was slowed down, such that by compensating for the reduced rotation, users performed a full 180 degree real-world rotation at each turning point. This way, a large virtual room could be explored while subjects walked back and forth between two ends of the tracked space.

The approach of adaptively increasing or decreasing the effective virtual motion to unnoticeably steer the user onto a desired real-world trajectory is called redirection with *dynamic motion gains*. To generalize the concept for arbitrary VEs, a number of improvements to the method have been proposed. *Steering algorithms* were developed, which compute dynamic motion gains based on universal heuristics [38,39], human motion models [40,41], or path-planning on a set of waypoints [42]. Another, more intrusive approach is the use of *distractors* in the virtual scene. Dynamically moving objects or agents are used to block the user's path and induce a turning motion [43], or to perform scene manipulations while the user is distracted [44,45]. Similarly, the phenomenon of *change blindness* is exploited to perform unnoticed scene manipulations. Examples include changing the placement of doorways when the user is not looking at them to create self-overlapping architecture [46,47] or perform slight scene manipulations during saccades [48] or blinks [49]. Different *perceptual illusions* have also been investigated for unnoticeable scene manipulations [50]. Recent work proposes the use of planar *map folding* that deforms the virtual floor plan to fit into the real-world boundary while maintaining local conformality and bijectivity of the warped space. In the following we focus on RDW techniques that modify the one-to-one mapping of real to virtual motion, either by employing explicit motion gains or by an implicit mapping as with the map folding approach. We consider these particularly prone to Cybersickness due to the sensory conflict between the visual and vestibular organs.

While many results have been achieved regarding the effectiveness of such RDW techniques, the problem of Cybersickness has only been addressed marginally. Most of the cited research does not present results regarding the effect on Cybersickness levels. Where quantitative measures are given, the lack of a control group experiment precludes from attributing the measured levels of Cybersickness to the employed RDW technique instead of the VE itself.

The initial work by Razzaque et al. mentions that subjects in their pilot study ($n = 11$) did not suffer any increase in simulator sickness [37]. The paper itself does not give any numerical evidence for the claim, however. Furthermore, the authors state that increased Cybersickness should not be caused, because "the technique keeps the visual, auditory and vestibular cues consistent". We object to that notion, in so far that the application of motion gains *does* cause an inconsistency between visual and vestibular cues, which we believe to be a major cause of Cybersickness symptoms. Later work restates the claim that additional Cybersickness caused by RDW techniques should not be significant for VR applications [51]. The sample size is derived for a power analysis to support that claim, which for the best case (an assumed SSQ population mean of 11 and an effect size of 5) requires $N = 266$ samples. Since at the time there was no capacity to conduct a study of that size, the claim remains unproven.

The notable work by Steinicke et al. on detection thresholds of motion gains does provide some measured SSQ data [52]. In the user study ($n = 14$), increased Cybersickness levels are reported, however from the given data it is not decidable whether the change was significant. The authors state that a follow-up experiment was conducted among subjects with "high Post-SSQ scores", but do not give any details about the experimental procedure. Another consideration with the reported values is that an SSQ was filled out once before and once after a series of three experiments. Although not explicitly stated, the order of experiments in the paper suggests that the experiment on rotation gain (E1) was performed first, and the Post-SSQ score was taken after all three experiments were completed, which took three hours overall according to the authors. Since rotation gains in particular have a strong effect on Cybersickness [33,53], it is possible that intermediate SSQ scores would have been much higher than the final Post-SSQ score suggests.

3 Method

In the following, the experimental design, the variables, the sample, as well as the analysis procedure are described.

3.1 Experiment Design

The experiment design was equivalent to the design described in Schmitz et al. [54]. Participants completed a preliminary questionnaire and completed four trials in a testbed environment while being redirected by dynamic rotational gains. A trial consisted of a target-collection task that had to be performed until the individual *threshold of limited immersion* [54] was reached. Subjects completed two trials in increasing and decreasing condition each, if they did not abort the experiment. Every participant was informed beforehand that undesirable side effects might occur and that they should not continue the experiment if they get uncomfortable, but they were uninformed about the applied redirection technique.

Fig. 1. View of the subject; 2 pillars are out of sight.

Participants with a medical history of epilepsy were excluded for safety reasons. Figure 2 shows an exemplary view on our testbed environment.

After the experiment, participants completed a post-questionnaire and a semi-structured guideline-based interview. The Simulator Sickness Questionnaire (SSQ) was completed at three times during the procedure: immediately before participants entered the VE (SSQpre), immediately after leaving the VE (SSQpost) and approximately 10 minutes later (SSQfinal).

3.2 Variables

We surveyed the following Human Factors in the preliminary questionnaire: gender, age, education degree, a VZ-2 paperfolding test as measure of mental rotation ability [55], self-efficacy towards technology (SET) [56], and the tendency to be immersed [7]. Furthermore we developed Likert scales to measure the subjective overall health condition, the experience with VR technology, and the tolerance for nauseous activities (e.g. riding a roller-coaster). In addition, we asked for self-reports on the own sense of direction and on overweight using a single Likert item each.

As evaluation criteria we surveyed perceived presence [7] and perceived immersion [57] as VR-related dimensions; enjoyment and anxiousness [58] as perceived emotions, as well as the behavioral intention scale of UTAUT2 as measure of technology adoption [59]. Furthermore, we operationalized trust in redirected walking (e.g. *"I feared to touch real objects or walls"* [negative item]) and the perception of the motion tracking as convincing (e.g. *"It felt strange to move around in the virtual environment"* [negative item]) in 5 items each.

3.3 Analysis Procedure

Self-reporting measures were transformed into pseudo interval scales if Cronbach's-alpha was above 0.5. SSQ total scores and sub-scores were calculated by summing up the symptom ratings and multiplying them with the according factors [23]. Since there is no interpretative meaning of SSQ score distances defined, we rely on non-parametric methods for statistical analysis.

Qualitative material was recorded and transcribed according to the well-established GAT2 system [60]. Those transcriptions were our sampling units. We define the answer on the question *"Under which circumstances would you endure general discomfort after VR usage?"*, as well as all further queries by the examiner to fully understand a answer recording unit. We defined a single phrase as smallest possible content unit and the whole answer as the context unit. To achieve high inter-coder agreement, the procedural approach of consensual coding was conducted [61]. We defined four main categories as initial category system: *Unmitigated preferences*, *application factors*, *symptom factors* and *other*. Four professionals took part in the coding procedure and assigned content units into those main categories independently as a first step. As a second step, they defined sub-categories that were determined inductively. Based on these four category systems, a consensual category system was elaborated and (re-)defined by all four coders. As a conclusive step, the overall material was assigned into this consensual system. The final results are unanimous.

3.4 Sample Description

Overall, 52 participants (50% female) took part in our study. The age of the participants ranged between 19 and 35 years ($M = 24.33$; $SD = 3.18$). 48% of the sample stated to own a high-school diploma, the other 52% reported to have obtained a higher education degree. In total, 12 participants (23.1%) aborted the experiment before reaching the final condition because of Cybersickness.

4 Results

In this section we describe quantitative and qualitative results of our study. We start by describing the dependent variables—SSQ nausea, oculomotor, discomfort and total score—as well as their inter-correlations. We further analyze Human Factors' influences on subjective evaluation criteria. The last subsection describes the results of the qualitative text analysis.

4.1 Quantitative Effects on Cybersickness

Description of SSQ Scales Table 1 shows descriptive statistics of the SSQ values for each time of measurement, as well as their differences in total scores and inter-correlations between the sub-scales nausea, oculomotor and disorientation at corresponding times. Since all sub-scales are heavily intercorrelated, we narrow down the further analysis to the interpretation of total scores. The average participant came to the experiment with $M = 16.18$ ($SD = 15.99$) points on SSQ total score, experienced a decrease in well-being to $M = 34.22$ ($SD = 39.51$) points and recovered to $M = 19.44$ ($SD = 20.91$) points 10 minutes after the experiment. Right after the experiment, there was no participant without any symptom of cybersickness at all (Min = 3.74, $M = 50.05$, $SD = 44.80$), and participants left with $M = 30.29$ ($SD = 39.58$) points on average. Furthermore, all total scores are intercorrelated: Higher symptoms before the VE exposure are significantly related to higher SSQ scores right after ($\tau = .41**, p < .01$) and higher SSQ scores 10 minutes after the experiment ($\tau = .40**, p < .01$). In addition, the two SSQ scores after the exposure are also positively associated ($\tau = .74**, p < .01$).

Table 1. Descriptives and Kendall-τ Intercorrelations for SSQ Subscales: TS = Total Score, N = Nausea, O = Oculomotor, D = Disorientation.

		Min	Max	M	SD	resp. Nausea	resp. Oculomotor	resp. Disorientation
SSQpre	Nausea	0	50.88	10.72	12.36	-		
	Oculomotor	0	90.96	18.42	19.67	.42**	-	
	Disorientation	0	64.96	11.4	14.89	.32**	.47**	-
	Total Score	0	71.53	16.18	15.99	.59**	.82**	.60**
SSQpost	Nausea	0	184.44	42.31	38.83	-		
	Oculomotor	0	146.55	36.6	33.46	.63**	-	
	Disorientation	0	296.96	57.91	60.46	.68**	.65**	-
	Total Score	3.74	222.00	50.05	44.80	.78**	.80**	.80**
SSQfinal	Nausea	0	146.28	25.18	33.45	-		
	Oculomotor	0	136.44	23.44	30.03	.68**	-	
	Disorientation	0	185.60	34.18	49.32	.75**	.66**	-
	Total Score	0	172.67	30.29	39.58	.84**	.81**	.82**
$\Delta SSQpost - SSQpre$	**Total Score**	-14.8	207.20	34.22	39.51	n/a	n/a	n/a
$\Delta SSQfinal - SSQpost$	**Total Score**	-86.3	29.60	-19.44	20.91	n/a	n/a	n/a

Note: Correlation columns show the sub-scales that correspond to the measuring time of the row. $^{*}p < .05$, $^{**}p < .01$.

The change in Cybersickness scores is quite visible in every sub-scale of the SSQ (see Fig. 4.1). The change in SSQ total score is significant according to Friedman's Anova ($\chi^2(2) = 51.61, p < .01$). Wilkoxon tests in pairwise comparison mode were used to follow up this finding. The SSQ score changed significantly from pre to post ($T = -1.25, p < .01$) and from post to final ($T = 1.12, p < .01$), but pre and final were not significantly different ($T = -.13, p = .51, n.s.$). A power-analysis was conducted on this last finding, yielding $1 - \beta = 0.55$. We therefore are not able to generalize difference or equality based on our sample and effect size.

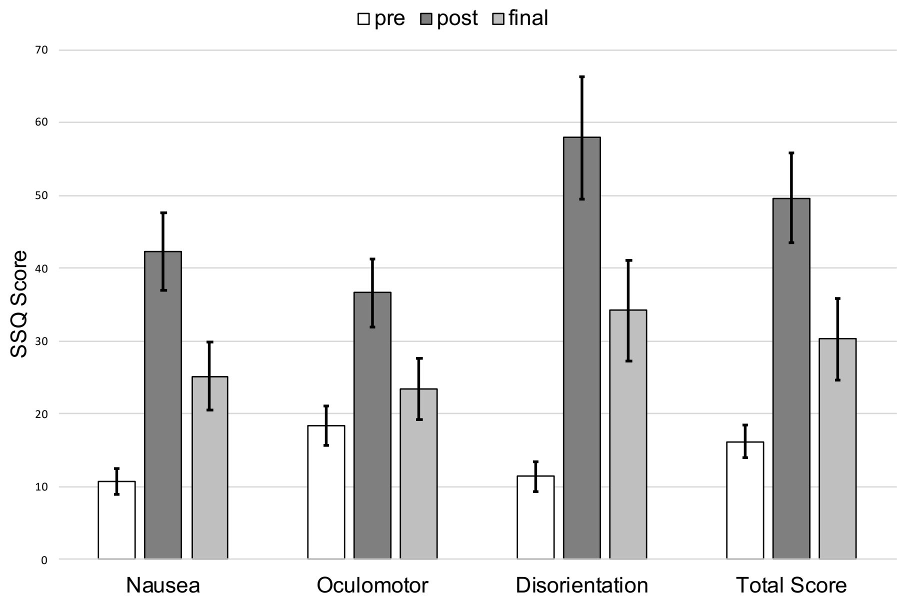

Fig. 2. Sub-scales and Total Score of SSQ among all times of measurement $\pm SE$. Important Note: The y-axis is cropped for readability reasons and every scale has a different theoretical maximum.

Effects of Human Factors When considering Human Factors, there are several significant correlations with SSQ scores. In line with theory, female gender is positively associated to Cybersickness, which is indicated by positive correlations between gender (dummy coded) and SSQpost ($\tau = .26*, p < .05$), SSQfinal ($\tau = .26*, p < .05$) and ΔPrePost ($\tau = .23*, p < .05$). A Mann-Whitney-U-test confirms this gender effect: Men were more resilient to symptoms of Cybersickness than women right after the experiment ($U = 461.50, p < .05$) and 10 minutes after the experiment ($U = 425.50, p < .05$). Furthermore, the increase in Cybersickness between men and women caused by the experiment was higher for women than for men ($U = 430.50, p < .05$). Other Human Factors, that are associated to gender, are also correlated to SSQpost and SSQfinal: With lower SET comes higher SSQpost ($\tau = -.21*, p < .05$) and higher SSQfinal ($\tau = -.26*, p < .05$), the same applies to a low perceived sense of direction ($\tau = -.23*, p < .05$, resp. τ=-.24*, $p < .05$). Other significant correlations with SSQ scores can be found between age and symptoms of Cybersickness before the experiment ($\tau = .23*, p < .05$), with younger participants having less symptoms. Apart from that, a better overall health condition was negatively associated to the SSQ score 10 minutes after the VR exposure ($\tau = -.26*, p < .05$).

Effects on Evaluation Regarding the subjective evaluation of the VR experience, several of the surveyed dimensions were associated to Cybersickness

Table 2. Kendall-τ Correlations between SSQ Total Score and Human Factors. $p* < .05$, $p** < .01$.

	α	M	SD	SSQpre	SSQpost	SSQfinal	ΔPrePost	ΔPostFinal
Gender	n/a	n/a	n/a		.26*	.26*	.23*	
Age	n/a	24.3	3.18	.23*				
Education	n/a	n/a	n/a					
VZ-2 Paperfolding	n/a	14.5	3.74					
HealthCondition	0.59	4.82	0.78			-.26*		
Experience with VR	0.78	2.95	0.66					
Tolerance for nauseous activities	0.74	3.96	1.16					
SET	0.83	4.26	0.83		-.21*	-.26*		
Immersion Tendency	0.62	4.08	0.73					
Perceived Sense of Direction	n/a	3.60	1.34		-.23*	-.24*		
Distance to Standard Weight	n/a	0.82	0.96					

Note: $*p < .05$, $**p < .01$, *Gender was dummy-coded with 1=male, 2 = female for correlation.*

(see Tab.3). Subjects who suffered more from Cybersickness right after leaving the VE experienced less presence ($\tau = -.19*, p < .05$) and less immersion ($\tau = -.21*, p < .05$), but these associations were not significant at the final measure. Additionally, a lower perception of enjoyment ($\tau = -.23*, p < .05$, resp. $\tau = -.28**, p < .01$) and a higher valuation of the motion as convincing ($\tau = -.25*, p < .05$, $\tau = -.28**, p < .05$) was associated to higher SSQ scores at both measuring times after the VR task. Surprisingly, a higher sense of anxiousness ($\tau = .43**, p < .01$, resp. $\tau = .45**, p < .01$) and a lower perception of trust ($\tau = -.27**, p < .01$, resp. $\tau = -.25**, p < .01$) was not just correlated to higher SSQ scores at both measuring times after, but also to the SSQ score even before entering the VE ($\tau = -.23*, p < .05$).

To further examine these findings, we calculated partial correlation: When we control SSQpre on the relationship between anxiousness and SSQpost resp. SSQfinal, we find the partial correlations to be still significant ($r = .51**, p < .01$, resp. $r = .40, p < .01$). This does not apply to the relationship between trust and these SSQ scores ($r = -.26, p = .06, n.s.$, resp. $r = -.19, p = .18, n.s.$).

Moreover, we found significant correlations between the first change in Cybersickness (ΔPrePost) and all surveyed dimensions except immersion and technology adoption: A higher increase in Cybersickess is associated to lower presence ($\tau = -.23*, p < .05$), lower enjoyment ($\tau = -.26*, p < .05$), lower trust ($\tau = -.24*, p < .05$), lower valuation of the motion as convincing ($\tau = -.21*, p < .05$) and higher anxiousness ($\tau = .40**, p < .01$). Furthermore, technology adoption was negatively associated to the final SSQ score ($\tau = -.20*, p < .05$).

Table 3. Kendall-τ Correlations between SSQ Total Score and Evaluation Criteria.

	α	M	SD	SSQpre	SSQpost	SSQfinal	ΔPrePost	ΔPostFinal
Presence	0.69	2.86	0.53		-.19*		-.23*	
Immersion	0.66	3.49	0.88		-.21*			
Enjoy	0.75	2.18	0.99		-.23*	-.28**	-.26**	
Anxiousness	0.74	1.46	0.96	.23*	.43**	.45**	.40**	-.22*
Technology Adoption	0.86	2.86	1.54			-.20*		
Trust	0.69	3.12	1.01	-.21*	-.27**	-.25*	-.24*	
Convincing Movement	0.58	2.34	1.00		-.25*	-.28**	-.21*	

Note: $*p < .05$, $**p < .01$.

4.2 Qualitative Role of Cybersickness

To complement our quantitative results, we report qualitative results in this section. Overall, we were able to identify 105 content units that could be assigned in the following categories.

Main Category 1: Unmitigated Preferences The sampling unit had to include an expression that Cybersickness would (or would not) be endured unexceptionally, to be assigned into this main category. We inductively developed the obvious subcategories *Unmitigated Endurance* and *Unmitigated Refusal*.

Unmitigated Endurance Only one content unit was covered by this category. The subject stated that she would "definitively use VR" even if symptoms occur, because she always endured the symptoms in previous VR experiences.

Unmitigated Refusal These units contained several arguments that were used to justify the answer, but we could not find any pattern that would justify the creation of another category layer. Subjects explained their refusal with the basic need to feel fine or stated that they would immediately abort the VR experience if Cybersickness arises. Others argued that they would not be capable to focus on the application anymore and some participants exclaimed that Cybersickness would just be "a no-go!" without any further justification.

Main Category 2: Effect of Application Context Being way more relevant to the research question than the first category, units had to contain statements that put endurance of Cybersickness in relation to the context of the VR-Application to be assigned in this category. We inductively developed two subcategories *Exciting Application*, *Serious Application* and *Extrinsic Motivation*.

Exciting Application Subjects argued that they would endure Cybersickness if the "fun-factor predominates the symptoms", or that they would endure it just like they endure motion sickness after a roller-coaster. The VR experience should be "exciting", "extremely innovative" or just an "intense video game" to compensate for the symptoms. Interestingly, some subjects answered the question in a way that they believe they would not even recognize Cybersickness if the application is entertaining enough.

Serious Application In contrast to the previous subcategory, some content units addressed serious applications instead of fun. Subjects argued that the VR experience should offer "some serious benefit" or "serve a good purpose". Three units mentioned very specific applications: Subjects would endure Cybersickness, if they would need to practice surgical operations in VR or if they could "quench their thirst for knowledge" by visiting the Louvre in Paris. Another unit contains the argument that VR could be necessary for work and adverse effects should therefore be endured.

Extrinsic Motivation Two participants mentioned extrinsic motivation as a condition to endure Cybersickness without mentioning specific application domains. They argued that they would tolerate discomfort if "they have to use the application" or for reasons of conscientiousness.

Main Category 3: Effect of Cybersickness Characteristics This main category contains units that include characteristics of the Cybersickness symptoms itself. We elaborated the category system by determining two subcategories: *Duration* and *Intensity*.

Duration Content units in this subcategory included arguments regarding the moment of occurrence or the duration of the symptoms. Subjects argued that they would endure Cybersickness if the symptoms were only present as long as the VE exposure lasts and not longer. Other subjects stated that the symptoms should not last longer than two hours, or that the symptoms should not occur continually, but only in singular peaks.

Intensity Subjects also stated that the intensity of the symptom should remain under a certain threshold. Cybersickness should be "still bearable" and "not too extreme". Another subject expressed the wish to examine the point, where she "can't take it anymore" and was optimistic "that it probably will get better after a certain habituation phase".

Main Category 4: Other Effects We found some content units that were not assignable in the previous categories and assigned them in three sub-categories: *Information about Cybersickness*, *Habituation* and *Cybersickness as Part of User Experience*.

Information about Cybersickness Two subjects stated that they would endure Cybersickness if they were well-informed that Cybersickness occurs at all, and furthermore can be sure that the reason for the symptoms "is just the algorithm and nothing serious".

Habituation Some subjects stated that they would endure the symptoms if they get the opportunity to experience Cybersickness more often to get used to the symptoms and to experience their individual threshold of discomfort.

Cybersickness as Part of User Experience Other units contained some interesting meta-aspects: Cybersickness might be accepted if the purpose of the VR application is to make the user resilient against Cybersickness, or even that Cybersickness might be part of the VE itself: Applications could deliberately induce Cybersickness to simulate drunk-driving and therefore raise awareness for responsible behavior in traffic.

Additional findings From a user experience perspective, it is noteworthy that subjects often used phrases like "I can't think of a specific application right now" or "I can't think of anything other than video games as applications". Apparently, users—even though younger and technology prone users volunteered in the study— still have difficulties to envision usage scenarios outside of their experience with VR applications and to contribute to user-centered requirements analysis of future applications.

5 Discussion

We conducted a user study where participants experienced a virtual environment with rotation gains as RDW technique, and measured Cybersickness with the well-established SSQ before, right after, and 10 minutes after the exposure. Results show that Cybersickness indeed arises, but also eases significantly after 10 minutes. Due to the size of the experiment, we can not conclude whether the symptoms reach the same level as before—the power of the experiment was only $1 - \beta = .55$. From other studies using VR and RDW we know that Cybersickness decreases quickly for some of the participants, yet others report of persisting symptoms for several hours. Apparently, there are considerable individual differences in how persons react to VR applications with Cybersickness symptoms. In this context, further research is required on Human Factors' influence on the recovery rate of Cybersickness as well as an understanding of the different responsiveness of users to sickness symptoms.

In contrast to the huge body of knowledge that individual variables and user diversity are central factors influencing the behaviors of and the attitudes towards novel technology [62,63,64,65], user factors showed only a marginal influence in this VR experiment. On the basis of the current data we can not conclusively explain the reasons for the small influence of individual variance. Speculating, two major arguments can be referred to in this context. On the one hand we only had a small and homogeneous sample, as all participants were young, highly educated, healthy, and technology savvy. Thus, the effect of user diversity could have been veiled as the differences were not detectable. On the other hand, one could speculate that the experience of rotational gains in VR environments might be unique for all participants in terms of physical reactions, and behaviors. Future studies will have to replicate the findings with more, and more diverse, participants.

However, we could replicate previous findings that women tend to be more susceptible to symptoms of Cybersickness than men at both times of measurement after the VR exposure. Obviously, women seem to be more responsive to physical and/or perceptual distortion effects. However, the higher sensitivity of women could also be a reporting bias. It is known from previous research that women are more sensible towards perception of bodily experiences, in line with a lower tolerance of pain sensations [66,67,68]. In addition to gender differences in physical perceptions, women could also be more open-minded to communicate somato-sensations and physical (dis-)comfort in contrast to men. On the base of the current data, we can not decide which of the two explanations, the physical (higher sensitivity to bodily stimuli) or the socio-cognitive explanation (a lower threshold to communicate bodily stimuli) might account for the gender differences in perception and/or communication of Cybersickness symptoms. While this distinction might be insightful from a psycho-physiological perspective, it is not relevant from a Human Factors perspective: Whenever there are gender differences in perception and acceptance of technology, technical designers need to consider those differences due to the claim of technology designs for all and universal access.

Furthermore, Cybersickness appeared to be stronger on subjects with low self-efficacy towards technology and subjects with low perceived sense of direction—which however are predominately women. Complementing the qualitative indication that Cybersickness was less relevant if the symptoms could be attributed directly to the redirection technique, we conclude that information about the specific applied redirection technique could be beneficial. Users who tend to feel insecure about technology might profit considerably from knowing that their symptoms are no reason to worry, but a result of their higher sensitiveness to sensory stimuli.

SSQ scores are highly subjective and even if it would be possible to quantify e.g. nausea objectively, the users' evaluation would still address the subjective perception. This points out a fundamental challenge for research on motion sickness, simulator sickness, and Cybersickness that uses the SSQ as a measure. While it is highly relevant to define a score that reflects the quality of a flight simulator for pilots, it is also highly domain specific with respect to both user and technology. The SSQ measure is therefore not necessarily suitable to evaluate the effects of Cybersickness in general VR applications for untrained users. A more reliable and generally applicable operationalization of Cybersickness is needed, possibly incorporating additional factors, such as objective physiological measures and symptoms that are not derived from motion sickness (e.g. impression of standing next to oneself or foreign body feeling caused by virtual body parts—out-of-body experiences).

In line with work by von Mammen et al. [11], our qualitative data raises the question of the relevance of Cybersickness as a predictor of the acceptance of VR. Similar to experiences such as roller-coaster rides, users conduct a trade-off evaluation of the benefits (e.g. fun) versus the potential costs (e.g. discomfort). This trade-off applies to professional contexts as well, as workers tend to go to work even if they feel ill. The endurance of Cybersickness could therefore also depend on the context and motivation to use VR. It would be highly relevant to understand how different users solve these trade-offs in distinct contexts. Furthermore, since we know that Cybersickness symptoms decrease with VR experience, future work should address to what extend this robustness is trainable. Human Factors that influence training progress should be investigated. The development of accepted VR applications that serve as Cybersickness habituation environments needs to be explored. Based on our data, such applications should not only be exiting, but also highly informative about possible VR benefits in different contexts as well as RDW techniques and the causes of Cybersickness in general.

6 Conclusion

We conducted a user study on the influence of Human Factors on Cybersickness levels in a VR environment that uses motion gains as a redirection technique. Participants were instructed to collect virtual pillars as long as they perceive their motion as natural, while we increased resp. decreased the rotation gain in discrete steps on every target collection. The experiment was finished after two conditions with decreasing gain and two conditions with increasing gain in randomized order. Before, right after, and 10 minutes after the VR-exposure, we measured symptoms of Cybersickness using the well-established SSQ. Furthermore we quantified demographic data, self-efficacy towards technology, ability of mental rotation, overall health condition, subjective sense of orientation, experience with 3D technology, tendency to be immersed, and tolerance for nausea inducing activities. Moreover, we measured perceived immersion, presence, trust, technology adoption, perception of realistic movement, enjoyment, and anxiousness as criteria of evaluation. The role of Cybersickness was furthermore examined via post-experimental qualitative interviews.

We came to the conclusion that Cybersickness and limited immersion are thresholds to be considered when implementing algorithms for redirected walking. Furthermore, future studies should investigate the influence of usage contexts on the acceptance of Cybersickness, as well as experimental paradigms to measure the intensity of rotational manipulation on which Cybersickness exceeds the acceptable threshold. In a final analysis, the cross-over effects when more than one redirection technique is used should be examined in order to implement an integrated approach that delivers high spatial compression and rich user experience.

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