Kelly, J.W., Hayes, N.L., Doty, T.A., Gilbert, S.B., & Dorneich, M.C. (in press). Profiles of cybersickness symptoms. *Displays*.

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Profiles of cybersickness symptoms

Jonathan W. Kelly[a,*], Nicole L. Hayes[b], Taylor A. Doty[a], Stephen B. Gilbert[c], Michael C. Dorneich[c]

[a] *Department of Psychology, Iowa State University, Ames IA, USA*
[b] *Department Social Science & Policy Studies, Worcester MA, USA*
[c] *Department of Industrial and Manufacturing Systems Engineering, Iowa State University, Ames IA, USA*

ARTICLE INFO

Communicated by XXXX

Keywords:
Virtual reality
Cybersickness
Motion sickness
Latent profile analysis
Individual differences
Simulator sickness questionnaire

ABSTRACT

Cybersickness – discomfort caused by virtual reality (VR) – remains a significant problem that negatively affects the user experience. Research on individual differences in cybersickness has typically focused on overall sickness intensity, but a detailed understanding should include whether individuals differ in the relative intensity of cybersickness symptoms. This study used latent profile analysis (LPA) to explore whether there exist groups of individuals who experience common patterns of cybersickness symptoms. Participants played a VR game for up to 20 minutes. LPA indicated three groups with low, medium, and high overall cybersickness. Further, there were similarities and differences in relative patterns of nausea, disorientation, and oculomotor symptoms between groups. Disorientation was lower than nausea and oculomotor symptoms for all three groups. Nausea and oculomotor were experienced at similar levels within the high and low sickness groups, but the medium sickness group experienced more nausea than oculomotor. Characteristics of group members varied across groups, including gender, virtual reality experience, video game experience, and history of motion sickness. These findings identify distinct individual experiences in symptomology that go beyond overall sickness intensity, which could enable future interventions that target certain groups of individuals and specific symptoms.

1. Introduction

Virtual reality (VR) promises to impact daily life through activities such as work, education, and entertainment. Yet, adoption of VR will be limited by cybersickness, or discomfort caused by VR exposure. Symptoms of cybersickness can vary across individuals and across types of exposure, but often include disorientation, nausea, sweating, headache, and eye strain. Cybersickness can occur relatively quickly, sometimes after just a few minutes of exposure. Up to half of users might experience at least some cybersickness within 20 minutes [1, 2, 3], and up to one quarter of users may experience severe cybersickness within just 10 minutes [4].

A complete description of cybersickness requires an understanding of how it manifests in the individual user. For example, understanding the cybersickness experiences of individual users could enable interventions that target specific individuals and their specific symptoms of cybersickness. Ideally, VR users would be provided with a cybersickness mitigation tool that targets the specific symptoms (e.g., nausea) that they are most susceptible to. However, little is known about whether individuals

*Corresponding author: Tel.: +1-515-294-2322
e-mail: jonkelly@iastate.edu (Jonathan W. Kelly), nhayes@wpi.edu (Nicole L. Hayes), tdoty@iastate.edu (Taylor A. Doty), gilbert@iastate.edu (Stephen B. Gilbert), dorneich@iastate.edu (Michael C. Dorneich)

http://dx.doi.org/10.1016/j.displa.xxxx.xx.xxx
Received 1 April 2024; Received in final form XXXX; Accepted XXXX; Available online XXXX

differ systematically in cybersickness symptom intensities.

The current study was conducted to understand whether there exist clusters of individuals who experience specific symptom constellations and intensities. To achieve this goal, this study used the statistical technique called latent profile analysis (LPA) to describe cybersickness experiences after exposure to a VR game.

2. Background

2.1. Cybersickness measurement

The most common method for measuring cybersickness is through subjective questionnaires administered after the VR experience, and the most common measure is the simulator sickness questionnaire (SSQ; [5]). The SSQ includes 16 self-report items, each with a different symptom rated on a scale from 0-3 (0 = none, 1 = slight, 2 = moderate, 3 = severe). Item scores are subsequently combined to produce four indicators of sickness: nausea symptoms, oculomotor symptoms, disorientation symptoms, and total sickness; the latter is a weighted combination of the three symptom subscales. Although the subscales overlap (a few items are assigned to multiple scales), they group well enough that many studies on cybersickness report data from the symptom-specific subscales. Other studies report only total sickness, depending on the goals of the research.

Although the SSQ is widely used to study cybersickness, it has also received criticism (see [6] and [7] for detailed descriptions of these criticisms). For example, the original data were gathered from military pilots using flight simulators. Another shortcoming of the SSQ is that direct comparison between subscales (e.g., to determine whether nausea is more prevalent than disorientation after VR exposure) is confounded by the manner in which the symptom subscales are calculated. SSQ subscales are computed by summing individual ratings (0-3) of the component items and multiplying the sum by a constant, which differs between subscales. Although the constants were meant to "produce scales with similar variabilities on which values can be more readily compared" [5], variability is likely to be affected by the population and stimulus, and the constants were not meant to equate the means. Since the constant is largest for disorientation (13.92), followed by nausea (9.54), followed by oculomotor (7.58), it is unsurprising that virtual reality has been reported to produce higher scores on the disorientation subscale than the nausea subscale, and higher scores on the nausea subscale than the oculomotor subscale [8, 9]. A hypothetical user who reports the same intensity (e.g., "moderate") for every symptom item on the SSQ would end up with this exact profile, despite reporting equivalent symptoms reflecting the experience of nausea, oculomotor, and disorientation. Reports that the symptom pattern caused by VR differs from other sickness-inducing stimuli, such as flight simulators [10], are more compelling, but comparison between symptom subscales within a given stimulus remains problematic.

Despite the aforementioned problems with the SSQ and its subscales, none of the proposed refactorings (e.g., [11, 12]) has gained substantial traction to replace the SSQ. The SSQ continues to be widely used, and therefore affords comparisons across current and past studies on cybersickness and related experiences.

Several single-item measures of cybersickness also exist, including the fast motion sickness scale (FMS) [13], the misery scale [14], and a dial-based indicator of sickness [15]. These measures provide real-time data about cybersickness that can inform decisions about when to provide cybersickness mitigation tools, such as field of view reduction [16], and when to recommend exiting the simulation. However, single-item measures do not capture symptom details, and therefore are less descriptive of the user's experience than symptom-specific measures. For example, two users might report the same level of discomfort (e.g., 6 out of 10) on a single-item measure but might have distinct experiences, with one primarily affected by headache and the other primarily affected by nausea. Understanding these symptom-specific experiences is critical to understanding cybersickness and can only be assessed by using symptom-specific measures.

2.2. Individual differences in cybersickness

Individuals vary in their experience of cybersickness. For example, women report greater sickness than do men [17, 18, 19, 20, 21, 9, 22]. Further, history of motion sickness and screen-based sickness positively associate with cybersickness [23, 19, 24, 17, 25], and have been found to partially mediate the relationship between gender and cybersickness [17]. Emerging research points to possible influences of other factors, such as personality [26, 27], on cybersickness.

Research on visually-induced motion sickness (VIMS, which includes sickness caused by VR and several other primarily visual experiences such as video games, movies, and simulators) indicates several predictive factors, including history of motion sickness as well as migraine, dizziness, faintness, and disorientation [28, 27, 29].

Experience with VR – another individual difference – corresponds to lower cybersickness ([30, 31, 32, 33, 19]; for a review, see [34]). For example, a 15-minute exposure to the same VR application across two separate days produced a 35-40% reduction in cybersickness on Day 2 relative to Day 1 [31, 32], with continued reduction over several subsequent exposures [35]. Still, it is unclear whether such adaptation generalizes beyond the specific VR experience [31, 30].

One study considered SSQ symptom subscales from an individual differences perspective [9]. Using a larger sample than is typical in VR research (N=960), the authors reported that women experienced significantly greater disorientation and oculomotor symptoms compared to men, but there was no gender difference in the experience of nausea. Conducing cross-group comparisons within a given subscale of the SSQ avoids the problems described in Section 2.1 when comparing across SSQ subscales. However, this topic of symptom profiles has received relatively little attention from the perspective of individual differences.

3. Study overview

It is well documented that individual differences in cybersickness severity are related to characteristics of the person,

such as gender [17, 18, 19, 20, 21, 9, 22] and prior history of sickness [23, 19, 24, 17, 25]. Yet, research on individual differences in cybersickness has typically focused on overall sickness intensity, combining symptom subscales of the SSQ into a total score or using single-item sickness measures that do not distinguish between multiple symptoms [23, 17, 20, 21, 22, 19]. A detailed understanding of individual differences in cybersickness should include whether individuals differ in the relative intensity of cybersickness symptoms.

To address this gap, a latent profile analysis was conducted to identify subgroups of participants with distinct symptom patterns. LPA is a model-based approach that identifies groups (i.e., latent profiles) using a probabilistic model that characterizes the distributions of each group and the likelihood that each item belongs [36]. Further, LPA provides fit indices that are useful for evaluating and comparing between models (e.g., comparing models that include one group versus two groups). The current study used LPA to examine the presence of such groups that share common patterns across cybersickness symptoms.

The analysis included the original SSQ symptom subscales as well as a novel reformulation of the subscales, referred to as raw intensity rating (details can be found in Section 4.4), which facilitates direct comparison between symptoms. Raw intensity ratings average together participant ratings of individual items that load onto a common factor, following the original factor structure of the SSQ [5]. This approach deviates from the original SSQ instructions to sum the items in a given subscale and multiply by a constant, which artificially increases some symptom subscales relative to others and obscures the original item scale (0-3, representing "none" to "severe").

Although the study was largely exploratory, the research and analysis plan was pre-registered here: `https://doi.org/10.17605/OSF.IO/3JHTG`

4. Method

4.1. Participants

There were 146 participants (73 men and 73 women; average age = 19.4, *SD* = 2.2). Participants were undergraduate students at Iowa State University who participated in exchange for course credit. Data collection occurred between August 2021 and May 2023.

4.2. Stimuli and Materials

Participants played Jurassic World: Aftermath, a VR game which was downloaded from the Meta Quest store. In this game, the player controls a character who has crash-landed on an island containing an abandoned dinosaur research facility. The player must explore the facility while evading dinosaurs to find information that will help them escape from the island. The game contains several small puzzles that are solved by exploring new areas of the environment. The game was chosen because of its "moderate" intensity rating on the Quest store. The participant was seated throughout the experience, and used joystick inputs via the Quest controllers to move and rotate through the environment. All comfort settings (e.g., teleporting [37, 38], or field of view restrictors [16, 39, 40, 41, 42]) were turned off. The game was experienced on either the Quest (*N*=62) or Quest 2 (*N*=84) headset, depending on when the participant enrolled in the study as the lab transitioned to more modern equipment.

Cybersickness was measured using the SSQ [5], a modified version of the Fast Motion Sickness Scale (FMS; [13]; modified by using a 0-10 scale), and time spent in VR. SSQ was the primary focus of the current analysis because it includes symptom-specific items, whereas FMS and exposure time are single-item measures of sickness. The SSQ was administered before and after the VR experience, and the FMS was administered every four minutes during VR exposure. SSQ scoring followed the original recommendations [5], including calculation of nausea, oculomotor, and disorientation scores, as well as a novel calculation of raw intensity rating to enable cross-symptom comparison. Only post-exposure SSQ data were used to evaluate cybersickness, in keeping with the original recommendations [5].

The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ; [43]) was used to measure previous sickness experiences due to screens. The Motion Sickness Susceptibility Questionnaire (MSSQ; [28]) was used to measure previous motion sickness experienced in vehicles and other forms of physical movement. Demographic information, including age and gender, was also collected.

4.3. Procedure

The participant arrived at the lab, provided informed consent, and completed several survey measures. The consent form indicated that the purpose of the study was to understand discomfort caused by VR. The survey measures included demographics, a video game experience survey, VIMSSQ, MSSQ, and SSQ. The researcher also measured the participant's inter-pupillary distance (IPD) using a ruler, and then adjusted the VR headset to match the measured IPD as closely as possible. The participant was then given basic instructions on how to perform the task (i.e., basics of how to play the VR game). The participant was then seated in a fixed-base chair, donned the VR headset. Participants were instructed to play for up to 20 minutes or until they could no longer continue due to sickness. During exposure, the experimenter verbally administered the FMS every four minutes and again at the time that exposure ended. The participant completed the SSQ immediately after VR exposure. The total time each participant spent in the lab was no more than 60 minutes.

4.4. Data analysis

Following best-practice guidelines [44], LPA was conducted to determine whether participants belong to different groups based on their reports of cybersickness symptoms. LPA was conducted on symptom subscales (nausea, oculomotor, and disorientation) following the original SSQ guidelines [5] as well as a novel reformulation of the subscales to enable comparison between symptoms. This reformulation, referred to as raw intensity rating, was calculated as the average rating of the component items recommended for each subscale of the SSQ. Using item averages directly reflects symptom intensity by retaining

Table 1. Fit statistics for the latent profile analysis (LPA) of cybersickness.

# Groups	AIC	BIC	SS BIC	Entropy	Adjusted LRT	BLRT	Grp 1	Grp 2	Grp 3	Grp 4
1	4402.83	4420.74	4401.75	NA	NA	NA	146			
2	4171.13	4200.97	4169.32	0.95	228.25, $p < .001$	239.70, $p < .001$	111	35		
3	4106.78	4148.56	4104.25	0.86	68.89, $p = .023$	72.348, $p < .001$	52	64	30	
4	4065.87	4119.57	4062.61	0.88	46.58, $p = .196$	48.92, $p < .001$	49	13	61	23

the 0-3 range and its associated meaning (0 = none, 1 = slight, 2 = moderate, 3 = severe), and enables meaningful comparisons across symptom subscales.

All LPA models were estimated in Mplus version 8.6 [45], using robust full information maximum likelihood estimation. This approach adjusts for standard errors and scales chi-square statistics to account for the non-normally distributed data. To avoid local solutions (i.e., local maxima) used 5,000 random starting values, 200 iterations for each random starting value, and the best 200 solutions were retained for the final stage of optimization. Mplus scripts and output are available on the Open Science Framework: `https://osf.io/y2ahm/`

Next, cybersickness symptoms were analyzed using ANOVA and paired comparisons to identify differences in symptom severity and symptom profile (i.e., the relative intensities of nausea, oculomotor, and disorientation) across the groups identified in the LPA.

Finally, characteristics of group members (e.g., gender, history of motion sickness) were compared across LPA groups using ANOVA and chi-square (in the case of categorical variables) to identify differences in group composition.

5. Results

LPA was conducted to determine whether participants belong to different profiles, or groups, based on their reports of cybersickness symptoms. This analysis was conducted first using the original SSQ subscales. Since no prior cybersickness research has used a similar data-driven clustering method, there are no theoretical grounds to prefer a specific number of groups. Therefore, selection of the best model was based on fit statistics and LPA best practices. We examined LPA models ranging from one to four groups to identify the optimal number of groups to retain (see Table 1). Model fit indices (AIC, BIC, and SSA-BIC) decreased, indicating better fit, as additional groups were added. The BLRT (bootstrapped likelihood ratio test) also indicated significant improvement with each added group. Yet, the LMRT (Lo-Mendell-Rubin test) indicated that while a three-group model provided a better fit than the two-group model, a four-group model did not provide better fit than a three-group model. Further rationale for preferring the three-group model over the four-group model was that the number of participants per group was more robust (over the recommended threshold of 25 participants; [46]) for the three- than the four-group model. Figure 1, top panel, shows SSQ score separately for the three groups identified in the LPA and three subscales corresponding to nausea, oculomotor, and disorientation.

The three-group model classified individuals with a high degree of accuracy. Classification accuracy ranged from 0.933 to 0.966, which is reflected in the relatively high entropy values in Table 1 (entropy values above 0.80 are considered desirable, [47]).

The LPA was also conducted using raw intensity rating, which allows for direct comparisons across symptom subscales. LPA results using raw intensity ratings were identical to those using SSQ subscales, presumably due to the fact that symptom averages are a linear transformation of SSQ subscales. Figure 1, bottom panel, shows raw intensity rating separately for the three groups identified in the LPA and three subscales corresponding to nausea, oculomotor, and disorientation. Visual comparison

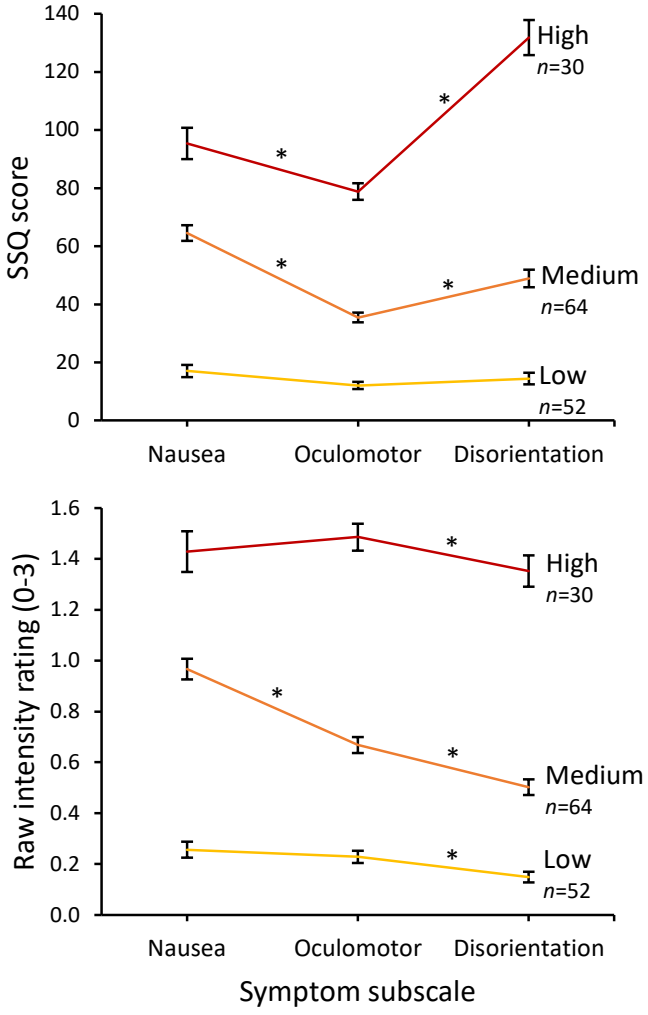

Fig. 1. SSQ score (top panel) and raw intensity rating (bottom panel) as a function of symptom subscale. Separate lines represent the low (yellow), medium (orange), and high (red) groups identified in the LPA. Error bars represent +/- 1 standard error. Asterisks indicate statistically significant pairwise tests, which are described in detail in the results section.

of SSQ scores and raw intensity ratings reveals distinct patterns across the subscales. Raw intensity ratings facilitate meaningful comparison across subscales, since the scores reflect the average of the component items on the original 0 ("none") to 3 ("severe") scale. In contrast, comparison of SSQ scores across subscales is biased by the unique multiplicative constant associated with each subscale. Subsequent results therefore focus on raw intensity ratings rather than SSQ subscales. Analysis of the original SSQ subscales can be found on the Open Science Framework: `https://osf.io/y2ahm/`.

As shown in Figure 1, Group 1 (n = 52, or 35.6% of the sample) was characterized by overall low intensity of nausea, oculomotor, and disorientation symptoms. Group 2 (n = 64, 44% of the sample) was characterized by medium intensity of nausea, oculomotor, and disorientation symptoms. Finally, Group 3 (n = 30, 20.3% of the sample) was characterized by overall higher nausea, oculomotor, and disorientation. The groups are therefore labeled as low, medium, and high, although such names ignore the possibility that differences among symptoms exist within and across groups. These differences are described next.

Raw intensity ratings were analyzed using ANOVA to identify different symptom patterns across the groups identified in the LPA. Cybersickness symptoms were analyzed in a mixed-model ANOVA with terms for symptom subscale (nausea, oculomotor, and disorientation) and group (low, medium, and high). ANOVA assumptions were satisfied except for the sphericity assumption, in which case Greenhouse-Geisser corrections were used. Significant main effects of symptom, $F(1.615, 286) = 24.412$, $p < .001$, $\eta_p^2 = .146$, and group, $F(2, 143) = 467.697$, $p < .001$, $\eta_p^2 = .867$, were qualified by a significant interaction between symptom and group, $F(3.230, 286) = 11.189$, $p < .001$, $\eta_p^2 = .135$.

In order to better understand symptom patterns for each group identified by the LPA, paired comparisons of raw intensity ratings were conducted separately by group. For the high sickness group, oculomotor intensity was greater than disorientation intensity, $t(29) = 2.164$, $p = .039$, $d = .395$. Nausea did not significantly differ from either oculomotor, $t(29) = 0.643$, $p = .526$, $d = .117$, or disorientation, $t(29) = 0.859$, $p = .397$, $d = .157$. For the medium sickness group, nausea was greater than oculomotor, $t(63) = 4.923$, $p < .001$, $d = .615$, nausea was greater than disorientation, $t(63) = 9.266$, $p < .001$, $d = 1.158$, and oculomotor was greater than disorientation, $t(63) = 4.481$, $p < .001$, $d = .560$. For the low sickness group, nausea was greater than disorientation, $t(51) = 3.500$, $p < .001$, $d = .485$, oculomotor was greater than disorientation, $t(51) = 3.810$, $p < .001$, $d = .528$, but nausea and oculomotor did not differ, $t(51) = .768$, $p = .446$, $d = .107$.

Final FMS (i.e., the final FMS value recorded upon ending VR exposure) and VR exposure time were also compared across LPA groups. Means and standard deviations are reported in Table 2. For FMS, the main effect of group was significant, $F(2, 143) = 41.987$, $p < .001$, $\eta_p^2 = .370$. The low group had lower FMS scores than the medium group, $t(114) = 6.928$, $p < .001$, $d = 1.293$, and the medium group had lower FMS scores than the high group, $t(92) = 2.774$, $p = .007$, $d = 0.614$. Final FMS correlated significantly with all SSQ symptom subscales (nausea: $r(144) = .630$, $p < .001$; oculomotor: $r(144) = .476$, $p < .001$; disorientation: $r(144) = .523$, $p < .001$). For exposure time, the main effect of group was significant, $F(2, 143) = 10.934$, $p < .001$, $\eta_p^2 = .133$. Participants in the low group had longer exposure time than the medium group, $t(114) = 2.987$, $p = .003$, $d = 0.558$, and the medium group had longer exposure than the high group, $t(92) = 2.025$, $p = .046$, $d = 0.448$. Exposure time correlated significantly with all SSQ symptom subscales (nausea: $r(144) = -.418$, $p < .001$; oculomotor: $r(144) = -.320$, $p < .001$; disorientation: $r(144) = -.325$, $p < .001$). A chi-square test revealed a significant difference across groups in the number of participants who were able to complete the full 20 minute exposure, $\chi^2(2) = 31.773$, $p < .001$, V = .466. Pairwise follow-up tests indicated that more participants in the low group completed the full exposure compared to the medium group, $\chi^2(1) = 11.895$, $p < .001$, V = .320, and that more participants in the medium group completed the full exposure compared to the high group, $\chi^2(1) = 9.169$, $p = .002$, V = .312.

Cross-group comparisons were conducted to further examine differences in group composition (see Table 2 for means and standard deviations). A chi-square test revealed a significant difference in gender composition across groups, $\chi^2(2) = 13.492$, $p = .001$, V = .304. Pairwise follow-up tests indicated that the low group was composed of fewer female participants compared to the medium and high groups (low-medium, $\chi^2(2) = 7.532$, $p = .006$, V = .255; low-high: $\chi^2(2) = 11.824$, $p < .001$, V = .380), but that the medium and high groups did not differ. A chi-square test revealed a marginally significant difference in VR experience across groups, $\chi^2(2) = 5.721$, $p = .057$, V = .198. Pairwise follow-up tests indicated that the high cybersickness group had fewer participants with VR experience compared to the low and medium groups (low-high, $\chi^2(2) = 5.832$, $p = .016$, V = .267; medium-high: $\chi^2(2) = 5.246$, $p = .022$, V = .236), but that the low and medium groups did not differ, $\chi^2(2) = 0.059$, $p = .808$, V = .023. The three groups significantly differed in video game hours per week, $F(2,143) = 4.055$, $p = .019$, $\eta_p^2 = .054$, with the medium group reporting fewer video game hours compared to the low group, $t(114) = 2.909$, $p = .004$, $d = 0.543$, and the high group, $t(92) = 2.222$, $p = .029$, $d = 0.492$. The groups significantly differed in VIMSSQ score (measuring history of visually-induced motion sickness), $F(2,143) = 7.146$, $p = .001$, $\eta_p^2 = .091$. The low group had lower VIMSSQ scores than the medium group, $t(114) = 2.204$, $p = .030$, $d = 0.411$, and the medium group had lower VIMSSQ scores than the high group, $t(92) = 2.097$, $p = .039$, $d = 0.464$. The groups also significantly differed in MSSQ score (measuring history of motion sickness), $F(2,142) = 6.925$, $p = .001$, $\eta_p^2 = .089$. The low group had lower MSSQ scores than the medium group, $t(113) = 2.622$, $p = .010$, $d = 0.491$, and the high group, $t(80) = 3.920$, $p < .001$, $d = 0.899$. The medium and high groups did not significantly differ in MSSQ, $t(91) = 1.434$, $p = .155$, $d = 0.318$. A chi-square test indicated that there was no difference in the distribution of Quest and Quest 2 headsets across groups, $\chi^2(2) = 1.266$, $p = .531$, V = .093.

Raw intensity ratings were also compared across symptoms without regard to group membership, in order to characterize

Table 2. Descriptive statistics for the three groups identified through LPA. Percentages are reported for categorical variables; means and standard deviations are reported for continuous variables. Superscript letters indicate statistical significance evaluated through post-hoc tests, where different letters indicate a statistically significant difference.

Grp	Women	VR exp	VG hrs	VIMSSQ	MSSQ	SSQ Total	FMS (0-10)	Time (min)	Full time
Low	30.8%[a]	17.3%[a]	25.42 (23.63)[a]	2.50 (2.25)[a]	7.62 (7.33)[a]	16.54 (1.49)[a]	3.48 (2.98)[a]	17.88 (4.25)[a]	80.8%[a]
Med	56.3%[b]	15.6%[a]	14.73 (15.77)[b]	3.39 (2.09)[b]	12.37 (11.23)[b]	64.54 (2.69)[b]	6.63 (1.89)[b]	15.16 (5.34)[b]	45.3%[b]
High	70.0%[b]	0.0%[b]	25.57 (31.61)[a]	4.43 (2.56)[c]	16.03 (12.14)[b]	95.40 (5.37)[c]	7.72 (1.45)[c]	12.89 (4.46)[c]	13.3%[c]

the overall and relative symptom severity after playing a VR game. A repeated-measures ANOVA with symptom subscale as the independent variable revealed a significant main effect of symptom, $F(1.561, 226.378) = 33.333$, $p < .001$, $\eta_p^2 = .187$. Nausea intensity ($M = .81$, $SD = .55$) was significantly higher than oculomotor intensity ($M = .68$, $SD = .51$), $t(145) = 3.515$, $p < .001$, $d = 0.291$, which was significantly higher than disorientation intensity ($M = .55$, $SD = .45$), $t(145) = 5.853$, $p < .001$, $d = 0.484$.

Finally, cybersickness was compared between the Quest and Quest 2 headsets. Raw intensity ratings did not differ significantly between headsets for nausea, $t(144) = .381$, $p = .704$, $d = 0.064$, oculomotor, $t(144) = .711$, $p = .478$, $d = 0.119$, or disorientation, $t(144) = .331$, $p = .741$, $d = 0.055$. FMS ratings also did not differ significantly between the two headsets, $t(144) = .033$, $p = .974$, $d = 0.006$. Means and standard deviations can be found on the Open Science Framework: `https://osf.io/y2ahm/`.

6. Discussion

LPA revealed three groups that differed in overall symptom severity (high, medium, and low) as well as symptom pattern. The medium-sickness group experienced more nausea than oculomotor, whereas the high-sickness and low-sickness groups experienced similar intensities of nausea and oculomotor symptoms. Disorientation was lower than oculomotor for all three groups. The finding that there exist three groups of people (not one, two, or four groups) with distinct symptom intensities and profiles is novel. Further, the intensity of symptoms experienced by the high group was 5 to 9 times larger (depending on the symptom) than that experienced by the low group. Whereas prior work on individual differences [23, 17, 20, 21, 22, 19] has typically focused on overall sickness intensity (e.g., by aggregating across symptoms or using single-item measures of sickness), these findings identify distinct individual experiences in symptom patterns.

The finding that groups of individuals experience different symptom profiles indicates that different people may benefit from distinct cybersickness mitigation measures. Common cybersickness mitigation tools include field of view restriction [40, 48, 16, 39, 42], static rest frames to provide a stable region within the visual scene [49] (but see [50]), and using the teleport interface [37, 38, 51, 52], whereby users are discretely repositioned without intermediate visual motion. The effect of these mitigation tools on specific symptoms warrants further exploration (most studies report only the effect on total sickness, not specific symptoms), but initial evidence indicates that disorientation, nausea, and oculomotor symptoms are not equally affected [40]. Ideally, cybersickness mitigation tools would be selected to match the user's specific needs based on symptom profile.

Characteristics of group members varied across groups. The high sickness group contained the most women, followed by the medium and low sickness groups. This is consistent with prior reports that women experience greater cybersickness than do men [17, 18, 19]. The groups also differed in VR experience and video game experience. VR experience was somewhat uncommon among the low and medium groups, but the high sickness group included no individuals with VR experience. Although the difference in prior VR experience between groups was marginal, it may reflect differences in adaptation to VR among members of the low and medium sickness groups [53, 32], or avoidance of VR among members of the high sickness group. Men are more likely than women to own VR headsets, but the difference in VR experience in the current study is not entirely attributable to gender differences, since 7 of the 19 participants who reported prior VR experience identified as female. Group differences also existed in video game hours per week, although the pattern did not logically follow the idea that those who play video games more would experience lower cybersickness [24, 54, 55] (but see [56]). Rather, the medium group reported fewer video game hours than the low and high groups, which did not differ. Future work might generate deeper insights by exploring the types of video games played [57] and the size and type of display used when gaming. VR games designations such as "Comfortable," "Moderate," or "Extreme" could be examined in future work to see whether these labels affect membership in the LPA groups. MSSQ and VIMSSQ scores, reflecting history of motion sickness and screen-based sickness, respectively, both directly mapped onto group membership (i.e., scores were highest among the high sickness group, lowest among the low sickness group, and medium in the medium sickness group). Collectively, these differences in group composition reflect many of the factors known to influence individual susceptibility to cybersickness [17, 54, 27, 31]. Ideally, a person's group membership could be predicted based on survey data, prior to the experience of potentially high levels of cybersickness. Knowing group membership would be useful for predicting overall symptom intensity as well as relative symptom profile. If such prediction were possible, then appropriate VR experiences and cybersickness mitigation tools could be offered, which seems like a promising direction for future work. Furthermore, future work should explore causal explanations behind the relationships identified between individual characteristics and cybersickness. Individual characteristics

can be difficult or impossible to manipulate, so researchers will need to rely on converging methodologies including experimental and longitudinal research.

Cybersickness research is shaped by the chosen measures. The SSQ [5] has been criticized on multiple levels, including the sample and stimuli used to generate the original data, as well as statistical issues around the factor analysis [6, 7]. Most relevant to the current project is that scores on the SSQ subscales reflecting nausea, oculomotor, and disorientation cannot be directly compared to one another because they are multiplied by different constants (see Section 2.1). To get around this issue, raw intensity ratings were computed by averaging the items that comprise each SSQ subscale, which also preserves the 0-3 rating scale. Visual inspection of the two panels in Figure 1 shows that the two scoring methods lead to different patterns of symptom intensity. For example, raw intensity ratings show that the medium sickness group experienced nausea more intensely than oculomotor, and oculomotor more intensely than disorientation (N > O > D). SSQ scores reverse the order of disorientation and oculomotor (N > D > O), but this is an artifact of multiplying SSQ subscales by the recommended constants, which shifts the true pattern of symptom intensity across subscales, leading to erroneous conclusions. For this reason, we recommend that future investigations of symptom-specific experiences of cybersickness avoid using SSQ scores to compare symptoms.

Some cybersickness studies have reported that severity of disorientation > nausea > oculomotor [8, 58, 32, 48, 59] when data are averaged across all participants. However, this pattern is at least partially driven by the multiplicative constants that are used when calculating SSQ subscales. Comparing raw intensity ratings in the current study revealed that the intensity of nausea > oculomotor > disorientation. More importantly, the finding that groups of participants exist with distinct symptom profiles indicates that an aggregate symptom profile, averaged across all participants, provides an incomplete description of cybersickness.

Details of the VR exposure likely influenced the pattern and intensity of symptoms observed in this study. Cybersickness was induced by playing a VR game with joystick locomotion, viewed on a Quest or Quest 2 headset. Gaming content and joystick locomotion are both associated with greater overall sickness [59, 60], and head-mounted displays cause vergence-accommodation conflict that influences oculomotor discomfort [59]. Other types of VR content and VR displays may induce distinct symptom patterns and result in distinct conclusions about individual differences.

Sickness did not differ between the Quest and Quest 2 headsets, despite technological differences between the two headsets. Past research indicates that headset frame rate [61] and resolution [62], factors that differed between the two headsets, are causally related to cybersickness. In one prior study [62], cybersickness was measured under four resolution conditions. Sickness in the lowest resolution condition was greater than in all other resolution conditions. However, the second-lowest resolution condition in that study included 2.6 times more pixels than the lowest resolution condition (the other two conditions were 6.9 and 11.2 times the lowest resolution condition). In contrast, the Quest 2 pixel count is 0.52 times that of the Quest, which may have been too small a difference to measurably affect cybersickness. In another study [61], cybersickness was measured with a headset running at 60, 90, 120, or 180 frames per second (fps). The only significant differences occurred between 120 and 60 fps in study 1 and between 180 and 60 fps in study 2. The Quest and Quest 2 frame rates are 72 and 90 fps, respectively, and this difference may have been too small to measurably affect cybersickness.

7. Limitations

This study used a consumer VR game to induce cybersickness, and this decision has advantages and disadvantages that affect interpretation of the findings. The primary advantage is that the stimulus is high in ecological validity: the game can be downloaded and played by Quest headset owners, and therefore represents an experience that closely compares to the experiences of VR users. A disadvantage is the lack of control over the stimulus. Participants had autonomy over how they moved (e.g., fast or slow locomotion) and where they traveled in the virtual environment. For example, one participant may have moved full-speed through the environment, generating lots of optic flow and quickly experiencing sickness, whereas another user might have used more careful and controlled movements to limit the stimulus intensity. Furthermore, a user who played the full 20 minutes would typically progress farther in the game than a user who dropped out after 5 minutes, and therefore would be exposed to additional parts of the game and environment. In fact, LPA group was significantly related to VR exposure time (low sickness group > medium sickness group > high sickness group). That is, participants who experienced greater cybersickness also withdrew from VR earlier. A more tightly controlled experiment could ensure more similar experiences across individuals. A small environment that can be quickly explored coupled with a repetitive task would ensure that most or all participants would experience the entire virtual world. Passive movement through the scene would further ensure consistency of the stimulus intensity. However, passive exposure to repetitive stimuli could also create additional confounding variables, such as boredom for those who stay longer in VR. Whether the latent groups identified in the current study might actually reflect differences in movement or exploration within the environment, which in turn might affect cybersickness symptoms, can only be answered through future work in which movement is recorded. It would also be important to distinguish whether individual differences in movement cause differences in cybersickness, or whether individual differences in cybersickness cause compensatory changes in movement. Movement was not recorded in the current study, yet the correspondence between the individual differences identified in the LPA (e.g., gender and history of motion sickness) and those identified using more tightly controlled visual stimuli [27, 54, 18] suggests that the LPA groups largely reflect characteristics of the person.

Another limitation to the study is the population from which participants were sampled. Recruitment of undergraduate psy-

chology students at a Midwestern university in the United States led to a limited age range that was younger than the typical VR user [2]. Age has been identified as an individual characteristic that may influence cybersickness [59]. Racial and ethnic diversity was also limited in this sample, and some evidence points to this as a predictive factor for cybersickness [63].

Another notable deficiency in the sample is that there were very few men (5.5%, compared to 46.6% of women) who reported 5 or fewer hours of gaming per week. Expanding this group in future research could reveal the relative impacts of gender and gaming experience on cybersickness.

8. Conclusions

Research on individual differences in cybersickness has typically focused on overall sickness intensity, but a detailed understanding should include whether individuals differ in the relative intensity of cybersickness symptoms. In this study, LPA revealed three groups with distinct experiences of cybersickness. These groups differed in overall sickness intensity as well as relative intensities of disorientation, nausea, and oculomotor symptoms. Characteristics of members also differed across groups, reflecting individual differences in the experience of cybersickness. These findings identify distinct individual differences in symptom patterns that go beyond overall sickness intensity, enabling future cybersickness interventions personalized to the individual user.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. 2309990.

Data availability

Data are available on the Open Science Framework: `https://osf.io/y2ahm/`.

References

[1] C. Yildirim, Don't make me sick: investigating the incidence of cybersickness in commercial virtual reality headsets, Virtual Reality 24 (2020) 231–239.

[2] J.W. Kelly, L.A. Cherep, A.F. Lim, T. Doty, S.B. Gilbert, Who are virtual reality headset owners? a survey and comparison of headset owners and non-owners, in: 2021 IEEE Virtual Reality and 3D User Interfaces (VR), 2021, pp. 687–694.

[3] L.A. Cherep, J.W. Kelly, A.J. Miller, A.F. Lim, S.B. Gilbert, Individual differences in teleporting through virtual environments, Journal of Experimental Psychology: Applied (2022).

[4] L.E. Garrido, M. Frías-Hiciano, M. Moreno-Jiménez, G.N. Cruz, Z.E. García-Batista, K. Guerra-Peña, L.A. Medrano, Focusing on cybersickness: pervasiveness, latent trajectories, susceptibility, and effects on the virtual reality experience, Virtual Reality 26 (2022) 1347–1371.

[5] R.S. Kennedy, N.E. Lane, K.S. Berbaum, M.G. Lilienthal, Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness, The International Journal of Aviation Psychology 3 (1993) 203–220.

[6] P. Bimberg, T. Weissker, A. Kulik, On the usage of the simulator sickness questionnaire for virtual reality research, in: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2020, pp. 464–467.

[7] V. Sevinc, M.I. Berkman, Psychometric evaluation of simulator sickness questionnaire and its variants as a measure of cybersickness in consumer virtual environments, Applied Ergonomics 82 (2020) 102958.

[8] K.M. Stanney, R.S. Kennedy, The psychometrics of cybersickness, Commun. ACM 40 (1997) 66–68.

[9] K.M. Stanney, K.S. Hale, I. Nahmens, R.S. Kennedy, What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience, Human Factors 45 (2003) 504–520.

[10] R.S. Kennedy, N.E. Lane, M.G. Lilienthal, K.S. Berbaum, L.J. Hettinger, Profile Analysis of Simulator Sickness Symptoms: Application to Virtual Environment Systems, Presence: Teleoperators and Virtual Environments 1 (1992) 295–301.

[11] W.B. Stone, Psychometric Evaluation of the Simulator Sickness Questionnaire as a Measure of Cybersickness, Ph.D. thesis, Iowa State University, 2017.

[12] S. Bouchard, G. Robillard, P. Renaud, et al., Revising the factor structure of the simulator sickness questionnaire, Annual Review of Cybertherapy and Telemedicine 5 (2007) 128–137.

[13] B. Keshavarz, H. Hecht, Validating an efficient method to quantify motion sickness, Human Factors 53 (2011) 415–426.

[14] J.E. Bos, S.N. MacKinnon, A. Patterson, Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view, Aviation, space, and environmental medicine 76 (2005) 1111–1118.

[15] N. McHugh, Measuring and minimizing cybersickness in virtual reality, Master's thesis, University of Canterbury, 2019.

[16] A.S. Fernandes, S.K. Feiner, Combating VR sickness through subtle dynamic field-of-view modification, in: 2016 IEEE Symposium on 3D User Interfaces (3DUI), 2016, pp. 201–210.

[17] J.W. Kelly, S.B. Gilbert, M.C. Dorneich, K.A. Costabile, Gender differences in cybersickness: Clarifying confusion and identifying paths forward, in: 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2023, pp. 283–288.

[18] M.C. Howard, E.C. Van Zandt, A meta-analysis of the virtual reality problem: Unequal effects of virtual reality sickness across individual differences, Virtual Reality 25 (2021) 1221–1246.

[19] T. Luong, A. Plechatá, M. Möbus, M. Atchapero, R. Bohm, G. Makransky, C. Holz, Demographic and behavioral correlates of cybersickness: A large lab-in-the-field study of 837 participants, in: 2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2022, pp. 307–316.

[20] D.M. Shafer, C.P. Carbonara, M.F. Korpi, Modern virtual reality technology: cybersickness, sense of presence, and gender, Media Psychology Review 11 (2017) 1.

[21] D.M. Shafer, C.P. Carbonara, M.F. Korpi, Factors affecting enjoyment of virtual reality games: a comparison involving consumer-grade virtual reality technology, Games for Health Journal 8 (2019) 15–23.

[22] K. Stanney, C. Fidopiastis, L. Foster, Virtual reality is sexist: but it does not have to be, Frontiers in Robotics and AI 7 (2020) 4.

[23] T.A. Doty, J.W. Kelly, M.C. Dorneich, S.B. Gilbert, Does interpupillary distance (IPD) relate to immediate cybersickness?, in: 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2023, pp. 661–662.

[24] L. Rebenitsch, C. Owen, Individual variation in susceptibility to cybersickness, in: Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology, UIST '14, Association for Computing Machinery, New York, NY, USA, 2014, p. 309–317.

[25] A. Jasper, N.C. Sepich, S.B. Gilbert, J.W. Kelly, M.C. Dorneich, Predicting cybersickness using individual and task characteristics, Computers in Human Behavior 146 (2023) 107800.

[26] A. Jasper, T. Doty, N. Sepich, M.C. Dorneich, S.B. Gilbert, J.W. Kelly, The relationship between personality, recalled cybersickness severity, and recalled cybersickness recovery time, in: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, volume 65, SAGE Publications Sage CA: Los Angeles, CA, 2021, pp. 206–210.

[27] J.F. Golding, A. Rafiq, B. Keshavarz, Predicting individual susceptibility to visually induced motion sickness by questionnaire, Frontiers in Virtual Reality 2 (2021).

[28] J.F. Golding, Predicting individual differences in motion sickness susceptibility by questionnaire, Personality and Individual Differences 41 (2006) 237–248.

[29] I. Lukacova, B. Keshavarz, J.F. Golding, Measuring the susceptibility to visually induced motion sickness and its relationship with vertigo, dizzi-

ness, migraine, syncope and personality traits, Experimental Brain Research 241 (2023) 1381–1391.
[30] I. Adhanom, S. Halow, E. Folmer, P. MacNeilage, VR sickness adaptation with ramped optic flow transfers from abstract to realistic environments, Frontiers in Virtual Reality 3 (2022).
[31] S. Palmisano, R. Constable, Reductions in sickness with repeated exposure to hmd-based virtual reality appear to be game-specific, Virtual Reality 26 (2022) 1–17.
[32] D. Risi, S. Palmisano, Effects of postural stability, active control, exposure duration and repeated exposures on hmd induced cybersickness, Displays 60 (2019) 9–17.
[33] R.S. Kennedy, K.M. Stanney, W.P. Dunlap, Duration and Exposure to Virtual Environments: Sickness Curves During and Across Sessions, Presence: Teleoperators and Virtual Environments 9 (2000) 463–472.
[34] N. Dużmańska, P. Strojny, A. Strojny, Can simulator sickness be avoided? a review on temporal aspects of simulator sickness, Frontiers in Psychology 9 (2018).
[35] P.A. Howarth, S.G. Hodder, Characteristics of habituation to motion in a virtual environment, Displays 29 (2008) 117–123.
[36] C. DiStefano, R.W. Kamphaus, Investigating subtypes of child development: A comparison of cluster analysis and latent class cluster analysis in typology creation, Educational and Psychological Measurement 66 (2006) 778–794.
[37] L.A. Cherep, A.F. Lim, J.W. Kelly, D. Acharya, A. Velasco, E. Bustamante, A.G. Ostrander, S.B. Gilbert, Spatial cognitive implications of teleporting through virtual environments., Journal of Experimental Psychology: Applied 26 (2020) 480.
[38] E. Langbehn, P. Lubos, F. Steincke, Evaluation of locomotion techniques for roomscale VR: Joystick, teleportation, and redirected walking., in: Proceedings of the Virtual Reality International Conference, ACM, New York, 2018, pp. 4:1–9.
[39] F. Wu, E. Suma Rosenberg, Adaptive field-of-view restriction: Limiting optical flow to mitigate cybersickness in virtual reality, in: Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology, VRST '22, Association for Computing Machinery, New York, NY, USA, 2022.
[40] M. Al Zayer, I.B. Adhanom, P. MacNeilage, E. Folmer, The effect of field-of-view restriction on sex bias in VR sickness and spatial navigation performance, in: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI '19, Association for Computing Machinery, New York, NY, USA, 2019, p. 1–12.
[41] J.W. Kelly, T.A. Doty, S.B. Gilbert, M.C. Dorneich, Field of view restriction and snap turning as cybersickness mitigation tools, PsyArXiv (2023).
[42] Y.X. Lin, R. Venkatakrishnan, R. Venkatakrishnan, E. Ebrahimi, W.C. Lin, S.V. Babu, How the presence and size of static peripheral blur affects cybersickness in virtual reality, ACM Transactions on Applied Perception 17 (2020).
[43] B. Keshavarz, B. Murovec, N. Mohanathas, J.F. Golding, The visually induced motion sickness susceptibility questionnaire (vimssq): Estimating individual susceptibility to motion sickness-like symptoms when using visual devices, Human Factors 65 (2023) 107–124.
[44] P. Sinha, C.S. Calfee, K.L. Delucchi, Practitioner's guide to latent class analysis: methodological considerations and common pitfalls, Critical care medicine 49 (2021) e63–e79.
[45] B. Muthén, L. Muthén, Mplus, in: Handbook of item response theory, Chapman and Hall/CRC, 2017, pp. 507–518.
[46] G. Lubke, M.C. Neale, Distinguishing between latent classes and continuous factors: Resolution by maximum likelihood?, Multivariate Behavioral Research 41 (2006) 499–532.
[47] T. Asparouhov, B. Muthén, Residual associations in latent class and latent transition analysis, Structural Equation Modeling: A Multidisciplinary Journal 22 (2015) 169–177.
[48] J. Teixeira, S. Palmisano, Effects of dynamic field-of-view restriction on cybersickness and presence in hmd-based virtual reality, Virtual Reality 25 (2021) 433–445.
[49] Z. Cao, J. Jerald, R. Kopper, Visually-induced motion sickness reduction via static and dynamic rest frames, in: 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2018, pp. 105–112.
[50] D. Zielasko, B. Weyers, T.W. Kuhlen, A non-stationary office desk substitution for desk-based and hmd-projected virtual reality, in: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2019, pp. 1884–1889.
[51] K.R. Moghadam, C. Banigan, E.D. Ragan, Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness., IEEE Transactions on Visualization and Computer Graphics 26 (2020) 2273–2287.
[52] T. Weissker, A. Kunert, B. Fröhlich, A. Kulik, Spatial updating and simulator sickness during steering and jumping in immersive virtual environments., in: Proc. IEEE Conference on Virtual Reality and 3d User Interfaces (VR), IEEE, Washington, D.C., 2018, pp. 97–104.
[53] M. Elwardy, H.J. Zepernick, Y. Hu, T.M.C. Chu, V. Sundstedt, Evaluation of simulator sickness for 360° videos on an hmd subject to participants' experience with virtual reality, in: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2020, pp. 477–484.
[54] P. Kourtesis, A. Papadopoulou, P. Roussos, Cybersickness in virtual reality: The role of individual differences, its effects on cognitive functions and motor skills, and intensity differences during and after immersion, Virtual Worlds 3 (2024) 62–93.
[55] S. Weech, S. Kenny, M. Lenizky, M. Barnett-Cowan, Narrative and gaming experience interact to affect presence and cybersickness in virtual reality, International Journal of Human-Computer Studies 138 (2020) 102398.
[56] D. Zielasko, A. Meißner, S. Freitag, B. Weyers, T.W. Kuhlen, Dynamic field of view reduction related to subjective sickness measures in an hmd-based data analysis task, 2024. URL: https://arxiv.org/abs/2403.07992. arXiv:2403.07992.
[57] L. Rebenitsch, C. Owen, Estimating cybersickness from virtual reality applications, Virtual Reality 25 (2021) 165–174.
[58] L. Rebenitsch, C. Owen, Review on cybersickness in applications and visual displays, Virtual Reality 20 (2016) 101–125.
[59] D. Saredakis, A. Szpak, B. Birckhead, H.A. Keage, A. Rizzo, T. Loetscher, Factors associated with virtual reality sickness in head-mounted displays: a systematic review and meta-analysis, Frontiers in Human Neuroscience 14 (2020) 96.
[60] P. Caserman, A. Garcia-Agundez, A. Gámez Zerban, S. Göbel, Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook, Virtual Reality 25 (2021) 1153–1170.
[61] J. Wang, R. Shi, W. Zheng, W. Xie, D. Kao, H.N. Liang, Effect of frame rate on user experience, performance, and simulator sickness in virtual reality, IEEE Transactions on Visualization and Computer Graphics 29 (2023) 2478–2488.
[62] J. Wang, R. Shi, Z. Xiao, X. Qin, H.N. Liang, Effect of render resolution on gameplay experience, performance, and simulator sickness in virtual reality games, Proc. ACM Comput. Graph. Interact. Tech. 5 (2022).
[63] A.J. Martingano, E. Brown, S.H. Telaak, A.P. Dolwick, S. Persky, Cybersickness variability by race: Findings from 6 studies and a mini meta-analysis, J Med Internet Res 24 (2022) e36843.