Sick in the Car, Sick in VR? Understanding How Real-World Susceptibility to Dizziness, Nausea, and Eye Strain Influences VR Motion Sickness

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Abstract. A substantial number of Virtual Reality (VR) users (studies report 30–80%) suffer from cyber sickness, a negative experience caused by a sensory mismatch of real and virtual stimuli. Prior research proposed different mitigation strategies. Yet, it remains unclear how effectively they work, considering users' real-world susceptibility to motion sickness. We present a lab experiment, in which we assessed 146 users' real-world susceptibility to nausea, dizziness, and eye strain before exposing them to a roller coaster ride with low or high visual resolution. We found that nausea is significantly lower for higher resolution but real-world motion susceptibility has a much stronger effect on dizziness, nausea, and eye strain. Our work points towards a need for research investigating the effectiveness of approaches to mitigate motion sickness so as not to include them from VR use and access to the metaverse.

Keywords: virtual reality · motion sickness · resolution

1 Introduction

Motion sickness is a common, negative experience many people suffer from, for example, in the form of seasickness on boats or dizziness when reading while driving. The same phenomenon occurs in Virtual Reality (VR): studies report that 30–80% of users experience motion sickness symptoms, depending on the type of virtual application [45,51]. While permanent damage is not known and severe symptoms are rather rare [21], symptoms ranging from dizziness, eye pain, and malaise, to vomiting can last for several hours [20].

Motion sickness has been a major challenge in VR since its inception and may likely turn into a major issue as we progress towards the vision of a metaverse to which head-mounted displays (HMDs) are likely to become a primary means of access [42]. A long history of prior research investigated factors and measures that influence motion sickness in VR, both from a *human* perspective as well as

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from a *software and technology* perspective. For example, much of the early work on VR looked into how motion sickness could be mitigated through technical improvements, such as higher resolution or shorter latency [53]. More recently, researchers investigated approaches of reducing motion sickness through aligning motion between VR and the real world [36] or visualizing motion flow in VR [11]. At the same time, it remains an open question how effective such measures are for people with a high susceptibility to motion sickness. In other words: *will people who easily experience real-world motion sickness experience lower cybersickness with technical mitigation strategies?*

This paper contributes a controlled lab experiment (N = 146), in which users suffering from motion sickness symptoms (disorientation, dizziness, nausea, eye strain) to varying degrees are exposed to a VR experience (i.e. a roller coaster ride) in one of two different resolutions. Our findings show that while nausea is significantly lower for high resolution, disorientation, and eye strain are hardly affected. At the same time, real-world motion sickness susceptibility has a much more pronounced effect on symptoms of motion sickness (disorientation, nausea, and eye strain). This suggests that the effect of mitigation strategies on users strongly differs based on personal factors, i.e. their motion sickness susceptibility.

We consider our work as a first step towards better understanding the interplay between users' susceptibility to different symptoms of motion sickness, and software- and technology-based mitigation approaches. Our findings reveal a need for a broader investigation of existing approaches to understand how VR environments of the future need to be designed so as to not exclude any users from a future in which VR might be a ubiquitous technology.

2 Background and Related Work

Our work draws from several strands of prior research: (1) motion sickness research, (2) factors causing motion sickness and their mitigation strategies, and (3) approaches to measuring cybersickness.

2.1 Introduction to Motion Sickness

Movement can be perceived physically and/or visually. In general, both types, even independently, can trigger motion sickness in people [4,39]. There is still disagreement in the scientific community about the exact cause of this anomaly [8]. However, it has been repeatedly found that people without a functioning vestibular organ or inner ear are immune to motion sickness [4,23,39]. Surprisingly, this is also true for purely visually induced motion sickness (VIMS) [4,10], that is the occurrence of motion sickness symptoms triggered solely by visual movement, in a physically static person [21].

The 'Sensory Conflict Theory' of Reason and Brand (1975) [43] states that conflicting signals from the sensory organs are the triggers for motion sickness [32,39]. This largely accepted approach has been steadily refined by studies. In

this context, every form of physical motion and each type of visual motion representation offers its own influencing factors on motion sickness. Speed, frequency, acceleration, and direction of motion are among the more obvious variables [4]. But also other influences, such as autonomous control of transportation, have an effect on motion sickness likelihood [54]. Accordingly, drivers are less susceptible than passengers as they anticipate motion to a certain extent, preparing the body for it [46]. Similarly, sitting in the opposite direction of travel increases motion sickness as being below deck increases sea sickness [54].

Visual fore-warnings of impending physical movement are limited here and do not allow for adjustment of physical anticipation. According to Mittelstaed [37], the discrepancy between expected and actual movement (termed "subjective vertical") is a trigger for motion sickness and is consequently elevated in passengers [4]. As explained, VIMS elicits a physiological response due to a purely visual stimulus. In contrast to physically induced motion sickness, it is the visual signals and not the vestibular organ that is primarily exposed to the stimuli [24]. The symptoms of affected individuals largely overlap with those of classic motion sickness and may eventually lead to vomiting. However, VIMS place a greater strain on the oculomotor system of the eye. Thus, affected individuals are more likely to report eye pain, blurred vision, and headaches [24].

Regardless of the type of motion sickness, the duration of movement exposure is relevant. Basically, the longer the person is exposed to the stimulus, the more likely and more intense the motion sickness symptoms will be [51]. Motion sickness symptoms are not currently measurable in purely hormonal or biochemical terms, although studies suggest a link to Melatonin levels [24]. In a recent paper, Keshavarz and Golding [26] mention that motion sickness has been the focus of attention in two contexts: automated vehicles, and VR. However, the focus is on either one of these two areas, and there is currently no efficient method to reliably prevent or minimize motion sickness (in real-time).

2.2 Motion Sickness in VR: Factors and Assessment Strategies

Motion sickness in VR is often referred to as *cybersickness* [52,59]. Prior research explored the reasons behind cybersickness in VR and the different ways it can be reduced or mitigated through the design of VR environments (cf. Davis et al. [13]). People experience cybersickness in VR with varying degrees, depending on personal aspects, application, and duration of exposure [49,60].

Prior work looked at individual differences in experiencing cybersickness. Influencing factors in VR include age [31], gender, illnesses, and posture [33,35]. VR motion sickness can be amplified or mitigated by the used VR hardware and software [48]. Latency, flicker, and poor calibration are all factors that may affect cybersickness in VR [35]. In addition to properties, such as frame rate, depth blur, and jitter, a study by Wang et al. [57] suggests that also resolution quality has an impact on motion sickness probability. Here, higher resolution seems to have a mitigating effect on motion sickness. Cybersickness can also occur because of the physical eye apparatus, e.g. vergence-accommodation conflict [3], and not just because of pure image perception.

Rebenitsch and Owen investigated the individual susceptibility to cybersickness [44]. Based on the data provided by the subjects (n = 20), they concluded that a previous history of motion sickness while playing video games predicted cybersickness best. A review by the same authors [45] summarizes state-of-the-art methods, theories, and known aspects associated with cybersickness: besides application design aspects, the influence of application design in general, field of view, and navigation are strongly correlated with cybersickness. The effect of visual displays is so far not well understood and needs further investigation.

The VR environment and task itself can affect cybersickness. McGill et al. [36] conducted an on-road and in-motion study (n = 18) to investigate the effects of different visualizations on motion sickness in VR. In a study by Chang et al. [9], they examined motion sickness in participants (n = 20) who were passengers in virtual vehicles and asked how motion sickness and the postural antecedents of motion sickness might be influenced by participants' prior experiences of driving physical vehicles. They showed that the postural movements of participants who later became seasick differed from those who did not. In addition, the physical driving experience during exposure to the virtual vehicle was related to the patterns of postural activity that preceded motion sickness. The results are consistent with the postural instability theory of motion sickness, which states that motion sickness is caused by loss of postural control [58]. An experiment (n = 20) by Carnegie and Rhee [7] was able to demonstrate that artificial depth blur reduces visual discomfort in VR HMDs. In this experiment, depth of field was integrated into the VR application by software, which simulates natural focusing by a dynamic blur effect. VR users view the center of the screen for about 82% of the time they are using the application. Therefore, an algorithm can detect the focus point of the eyes to a certain degree and adjust the blur accordingly. However, it has not been possible to imitate natural vision completely with this method. Park et al. [41], investigated the relationship between motion sickness in VR and eye and pupil movements through a user study (n = 24). It was found that participants showed irregular patterns of pupil rhythms after experiencing motion sickness in VR using HMDs. Based on this data, a method able to quantitatively measure and monitor motion sickness in real time using an infrared camera was proposed. However, this has neither an influence on the perceived motion sickness of the user nor on reducing it.

2.3 Measuring Cybersickness

Somrak et al. used the Simulator Sickness Questionnaire (SSQ) in combination with the User Experience Questionnaire (UEQ) [34,47] in a user study (n = 14) conducted in 2019 [50]. Other research explored the use of physiological measures such as EEG, heart rate [38], respiration rate [30], and skin conductance, to measure sickness in VR. In a recent study by Garrido et al. [16], focused on the examination of the cybersickness phenomenon, 92 participants experienced a ten-minute VR immersion in two environments. The results showed that even with new HMDs, 65.2% of the participants experienced cybersickness, and 23.9% experienced severe cybersickness. In addition, susceptibility to motion sickness,

cognitive stress, and recent headaches clearly predicted higher severity of cybersickness, while age showed a negative association [16] (see Table 1).

Table 1. Overview of Prior Work including User Studies

Focus of Prior Work	Authors	Sample
Investigates the resolution trade-off in gameplay experience, performance, and simulator sickness for VR games	Wang et al. [57]	16
Investigation of the individual susceptibility to cybersickness	Rebenitsch and Owen [44]	20
On-road and in-motion study investigating effects of different visualizations on VR sickness	McGill et al. [36]	18
Integrates depth of field into VR application, simulating natural focus by a dynamic blur effect	Carnegie and Rhee [7]	20
Investigates the relationship between motion sickness in VR and eye and pupil movements	Park et al. [41]	24
User study of the effects of VR technology on VR sickness and user experience	Somrak et al. [50]	14
Examines the cybersickness phenomenon in a ten-minute VR immersion in two environments	Garrido et al. [16]	92

Most studies considered measuring cybersickness/motion sickness in VR, utilizing self-reported standardized questionnaires, such as the widely adopted Simulator Sickness Questionnaire (SSQ) [25]. Golding [18,19] introduced the Motion Sickness Susceptibility Questionnaire (MSSQ) to predict an individual's susceptibility to motion sickness, based on a person's past history of motion sickness as a child or adult. Other questionnaires include the Virtual Reality Symptom Questionnaire [1], the Virtual Reality Sickness Questionnaire (VRSQ) [29], and single-item questionnaires, such as that from Bos et al. [5]. A more recently introduced questionnaire is the six-item Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ/VIMSSQ-short) by Golding et al. (2021) [17], which is based on the SSQ [25]. The VIMSSQ is a useful complement to the MSSQ in predicting visually induced motion sickness. Other predictors are migraine, syncope and social and work impact of dizziness [28]. Also more recently, and closely related to our current work, Freiwald et al. [15], introduced the Cybersickness Susceptibility Questionnaire which is meant to be administered *before* the VR experiment so as to predict cybersickness that may be experienced by participants. Table 2 provides an overview of these questionnaires.

2.4 Summary

Our work differs from this research in several ways: first, we explore the relationship between real-world motion sickness susceptibility and sickness in VR in

Table 2. Overview of Existing Questionnaires

Name	Author(s)	Year
Simulator Sickness Questionnaire (SSQ)	Kennedy et al. [25]	1993
Motion Sickness Susceptibility Questionnaire (MSSQ)	Golding, JF [18]	1998
Virtual Reality Symptom Questionnaire	Ames et al. [1]	2005
Virtual Reality Sickness Questionnaire (VRSQ)	Kim et al. [29]	2018
Cybersickness Susceptibility Questionnaire (CSSQ)	Freiwald et al. [15]	2020
Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ/VIMSSQ-short)	Golding et al. [17]	2021

a large-scale study (n = 146). Additionally, we investigate particular symptoms of motion sickness (disorientation, nausea, eye strain). Finally, we compare the effect of resolution as a technology-based factor relating to cybersickness, to the personal-based factor of susceptibility to motion sickness in the real world.

3 Research Approach

3.1 Research Questions and Hypotheses

Motion sickness susceptibility depends on the stimulus and the individual person [19]. VR environments can trigger visually induced motion sickness [21]. An individual's prior motion sickness experience is considered a valid measurable predictor of their susceptibility [18]. Accordingly, hypothesis H1 assumes that triggered by the VR stimulus, the general individual motion sickness susceptibility is reflected in the form of motion sickness symptoms:

H1 Users who are more susceptible to motion sickness in everyday life show stronger motion sickness symptoms after being exposed to a VR experience.

In addition to H1 investigating personal aspects, we investigate the interplay between real-world susceptibility and resolution which was shown to have an effect on motion sickness in VR [57]. By investigating how resolution affects motion sickness, we can better understand how the visual system contributes to the development of motion sickness symptoms. We test the following hypothesis:

H2 Users who experience a VR environment in high resolution will exhibit lower motion sickness symptoms after testing than users who experience a VR environment in lower resolution.

In addition to the type of stimulus, personality-related factors are crucial for motion sickness symptoms [19]. Known motion sickness triggers such as vertical, jerky, and simulated self-motion are essentially unaffected by resolution quality. Considering previous studies, the effect size of resolution quality on motion sickness is comparatively smaller [57]. We hypothesize the *type* of motion sickness

susceptibility to have a greater influence on motion sickness symptoms than resolution quality. The groups with motion sickness-susceptible participants would thus be expected to have the strongest symptoms, followed by test condition type. Hypotheses H3a-d subsume this assumption:

H3a The test group with increased motion sickness susceptibility and low-resolution quality (T1b) will exhibit the strongest post-test VR motion sickness symptoms.
H3b The test group with increased motion sickness susceptibility and high VR device resolution (T1a) exhibits the second most severe symptoms.
H3c The test group with low motion sickness susceptibility and low VR device resolution (T2b) exhibits the third most severe symptoms.
H3d The test group with low motion sickness susceptibility and high VR device resolution (T2a) exhibits the least severe symptoms.

3.2 Apparatus

To investigate the research questions and test the hypothesis, we chose the HTC VIVE Pro 1. This VR device was chosen for its comparably high resolution (2880 × 1600 pixels) and large field of view (110°) at the time. The tracking is enabled by two external infrared sensors.

According to our literature review of motion sickness and prior work, we identified several factors that need to be considered when building a VR application for testing our hypothesis. First, passengers are more prone to motion sickness than drivers. Vertical, jerky movements with rapid changes in direction are also strongly conducive to motion sickness. For comparability of the stimuli, replicable runs with the same runtime should also be possible. Therefore, interactive VR game mechanics were unsuitable. We chose the application 'Motor-ride Roller-coaster VR' from the developer *Split Light Studio*[1], offered on the gaming platform *Steam*, as it fulfills the aforementioned criteria. The VR experience simulates a predefined motorcycle ride through rough terrain.

An evaluation of Steam user reviews suggests a strong motion sickness-inducing experience overall (Valve Corporation, 2020)[2]. To reflect the different test conditions in resolution quality, the graphics settings are changed. Using the Steam VR driver, Condition A (High Resolution) displays the full total resolution of 2880 × 1600 pixels, and Condition B (Low Resolution) reduces this to 2228 × 1237 pixels (-23%). This roughly corresponds to the resolution of an HTC Vive 1st generation. The effect of the reduced resolution quality is additionally intensified by the graphics settings of the VR application. Thus, in condition B, texture resolution, edge smoothing (anti-aliasing) and anisotropic filtering were reduced to the lowest level, resulting in a visual difference in color dynamics and saturation. The test conditions thus differ noticeably in the overall impression

[1] https://store.steampowered.com/app/1346890/Motoride_Rollercoaster_VR/.
[2] https://steamcommunity.com/app/1346890/reviews/?p=1&browsefilter=mostrecent.

of the resolution quality and color representation (see Fig. 1). Regardless of the condition, the frame rate was constantly set to 60 FPS and the refresh rate to 90 Hz. Graphics settings regarding the viewing distance or field of view also remained unaffected. The purely software-based modification of the test conditions also excludes a possible influence by different VR HMD models. Still, the same VR HMD was always used in the subsequently described experiment.

(a) Condition A: Sample–High Resolution (b) Condition B: Sample–Low Resolution

Fig. 1. Sample screens from the high and low-resolution conditions

3.3 Questionnaires

During the study, we used several questionnaires. During the *initial questionnaire* (cf. Table 3), we first assessed whether participants owned a VR HMD and how familiar were with VR in general (I1, I2). In addition, we asked how they currently felt (I3). We then assessed their susceptibility to dizziness (I4) and nausea (I5) using the MSSQ and had them self-assess (I6) how strongly they felt to be susceptible to motion sickness. Therefore we used Golding's (1998) revised MSSQ [18]. Specifically, for consistency we used a 7-Point Likert scale and reduced the number of items by focusing on those relevant to VR motion sickness symptomatology, according to the purpose of the study.

In the *post-VR stimulus questionnaire* (cf. Table 4), we first asked them whether they completed the experience (P1). Then, using the VRSQ [29], we assessed disorientation (P2a), nausea (P2b), and eye strain (P2c). Again, we used a 7-Point Likert scale. Afterwards, we assessed the perceived hedonic benefits (P3a), telepresence (P3c), exploratory behavior (P3d), and attractiveness of the stimulus, using the UEQ (P3e). This block also contained an attention check (P3b)The questionnaire concluded with demographic questions (P4) and whether they had any suggestions or comments about the experiment (P5).

4 User Study

We designed a 2×2 between-subjects study with resolution and susceptibility as independent variables. Participants were assigned to either the `High Resolution` (A) or `Low Resolution` (B) condition. The split into the `High Susceptibility` or `Low Susceptibility` conditions was done during the evaluation.

4.1 Procedure

The study was conducted in a quiet lab room in which the VR HMD setup was prepared. Participants were first introduced to the study and signed a consent form. Then, they filled out the first questionnaire. After completing the first questionnaire participants were randomly assigned to test condition A – High Resolution or condition B – Low Resolution. Equal distribution was ensured. Subjects then run through the respective VR stimulus. After the end of the task, participants answered a second questionnaire, including a subjective evaluation of motion sickness symptoms that may have arisen during or after the VR stimulus. The motorcycle ride application lasts exactly 6:20 min and seamlessly covers three different environments. Hints about the upcoming route are not possible and direction changes are usually unexpected. Beyond fast and slow motion passages, jumps and turns additionally vary the displayed speed. The application thus is different from roller coaster simulations in that it is less predictable. However, the user cannot intervene on the track. The seated VR experience offers 3-DoF and puts the user in a purely observational position.

The total duration including the questionnaire amounts to 15 min per participant, including appr. 6 min for the motorcycle ride (Fig. 2).

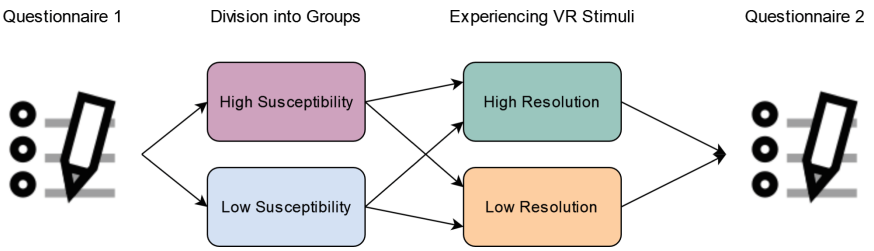

Fig. 2. Study Procedure

4.2 Study Limitations

Although there are several influencing factors that can trigger motion sickness (visual and auditory), the focus here was on visually induced motion sickness, as

Table 3. Questionnaire 1: Before VR Stimulus

Construct	Question	Statement
I1	Do you own a VR HMD?	- Yes: model (+open statement)
		– No, not anymore
		– No
I2: Involvement	Please indicate the extent to which you agree or disagree with the following statements. (Likert 1–7) [Strongly disagree – Strongly agree]	– I already experienced VR
		– I have access to a VR HMD
		– I use VR HMD regularly
		– I use VR HMD regularly
		– I generally enjoy VR experiences with a VR HMD
I3: Feeling	How are you feeling right now? (Likert 1–7) [Not at all – Very much]	– Hungry
		– Thirsty
		– Weak
		– Full of energy
		– Tired
		– Awake
		– Relaxed
		– Stressed
I4: Susceptibility to Dizziness (MSSQ) [18]	Do you generally tend to experience: (Likert 1–7) [Not at all – Very strongly]	– Dizzy spells
		– Dizziness:
		– when flying
		– while driving a car
		– while watching television
		– while reading while driving
		– Seasickness
I5: Susceptibility to Nausea (MSSQ) [18]	Do you generally tend to experience: (Likert 1–7) [Not at all – Very strongly]	– Fear of heights
		– Nausea:
		– while riding a train
		– while driving a car (passenger)
		– while flying
		– while watching television
		– while reading while driving
I6: Self-assessment (MSSQ) [18]	Rate yourself as: (Likert 1–7) [Not at all – Very much]	– Susceptible to motion sickness?

this exerts the strongest impact on the overall experience [27]. However, there are several ways in which motion sickness can be induced visually, such as movements in the real world that do not translate properly in VR, or movements in VR that have no relation to the users' movements in the real world. In our study, we decided to use an application that builds on the first mentioned approach because this type of motion sickness is much more prevalent than other ways of inducting motion sickness [28]. We decided to choose a VR game to be able to

Table 4. Questionnaire 2: After VR Stimulus

Construct	*Question*	*Statement*
P1:	Did you complete the VR experience to the end?	– Yes – No, I stopped at approx. minutes: (+open indication).
P2a: Disorientation (VRSQ) [29]	Did you feel after, or during the testing: (Likert 1–7) [Not at all - Very much]	– Dizziness – Orientation problems
P2b: Nausea (VRSQ) [29]		- Nausea – Sweating
P2c:Eye Strain (VRSQ) [29]		– Headache – Problems with focusing (vision) – Eye Strain
P3a: Hedonistic benefits [55]	Please indicate the extent to which you agree or disagree with the following statements. (Likert 1–7) [Not agree at all - Fully agree]	– The VR experience was fun – The VR experience was entertaining – The VR experience is a good way to pass the time
P3b: Attention		– To show that you are still attentive, click here value 'two'
P3c: Telepresence [22]		– It felt like I was actually in the VR environment – It felt like everything I saw was real – I lost track of time during the VR experience
P3d: Exploratory behavior (Flow) [12]		– I appreciate unique VR experiences – VR experiences feel like exploring a new world – I would like to know more about VR experiences
P3e: Attractiveness (UEQ) [34]		– I find wearing a VR HMD comfortable – I could easily use a VR HMD for a longer period of time at a stretch
P4:	Demographics	– Age – Gender – Education – Occupation
P5:	Do you have any suggestions or comments about the experiment?	– (open statement)

compare to other VR studies, as games are readily used here to investigate, for example, navigation techniques and interaction techniques [2]. However, we do acknowledge that investigations in other contexts might yield different results.

There are high-end VR headsets with higher-resolution displays available at the moment. Yet, we decided to focus on affordable consumer VR HMSs. With a resolution of 1440 × 1600 pixels per eye, a refresh rate of 90 Hz, and a field of view of 98°, the HTC Vive Pro 1 is still one of the best consumer devices [6].

Finally, the correlation between age and motion sickness susceptibility is scientifically controversial [14,16,40]. Our sample mainly consisted of students.

Therefore, future work may want to look into different age groups to verify whether the findings generalize to a broader population.

5 Results

5.1 Demographics and Motion Susceptibility Condition Assignment

We recruited 151 volunteers for the study via internal university mailing lists, social media, and personal contacts. Sweets were offered as an incentive. As the study was conducted on campus, the vast majority of participants were students.

Five participants who failed to correctly answer the attention check question (see Table 4) were removed. Our final data set consisted of 146 participants (54 female, 92 male, mean age 24), of which 72 were assigned to Condition A – High Resolution and 74 were assigned to Condition B – Low Resolution. Only 11 (7.5%) of the participants reported owning a VR HMD.

Premature discontinuation of the VR stimulus due to symptoms does not lead to exclusion from the study. A corresponding item in the second questionnaire records cessation or discontinuation at the respective test minute. 22 participants (15.1%) terminated the VR stimulus prematurely. Broken down by test condition, 11 of these belong to test condition A and 11 to condition B. The average termination time is minute 3:19 *after* the start of the VR stimulus.

A researcher observed and noted down symptoms during data collection. Participants' symptoms ranged from no symptoms at all to severe malaise and nausea. In condition B, poor graphics quality was sporadically mentioned.

Deriving the Motion Sickness Susceptibility Condition. For a computational test of the stated hypotheses, new variables are established from the dataset (Table 5). Items for self-assessment of motion sickness susceptibility of dizziness, nausea, and general susceptibility were merged under the new variable 'Motion Sickness Susceptibility'. Similarly, the items for motion sickness symptoms recorded after the VR stimulus, categorized into disorientation, nausea, and eye strain, were computed as 'Motion Sickness Symptoms Combined'. Reliability analysis by Cronbach's alpha value is performed before combination.

Categorizing Participants in Susceptibility Condition. To categorize participants according to their susceptibility type, the mean and median of all tested participants are considered (Table 6). Subjects with a motion sickness susceptibility of $<= 1.923$ are categorized as *Low Motion Sickness Susceptibility* and >1.923 as *High Motion Sickness Susceptibility*.

5.2 Influence of Real World Motion Sickness Susceptibility

Correlation analysis of the variables `Motion Sickness Susceptibility` and `Motion Sickness Symptoms Combined` investigates the relationship suspected

Table 5. Merging the Variable Categories on a Mean Value Basis

Construct	Statement	Cronbach's α	New Variable
Merge of Motion Sickness Susceptibility (before VR stimulus)∗			
Susceptibility to dizziness	Dizzy spells in general Dizzy when flying Dizzy while driving a car Dizzy while watching television Dizzy when reading while driving Seasickness	.908	Motion Sickness Susceptibility
Susceptibility to nausea	Fear of heights Nausea while riding a train Nausea while riding a car (passenger) Nausea while flying Nausea while watching television Nausea when reading while driving		
Self-Assessment	Susceptible to motion sickness		
Merge of Motion Sickness Susceptibility (after VR stimulus) ∗			
Symptom Disorientation	Dizziness Orientation problems	.809	Disorientation
Symptom Nausea	Nausea Sweating	.889	Nausea
Symptom Eye Strain	Nausea Sweating	.830	Eye Strain
Disorientation Nausea Eye Strain		.823	Motion Sickness Symptoms Combined

∗ *based on mean values*

Table 6. Classification into Motion Sickness Susceptibility Types by Median

Susceptibility Type	N	Percent	Mean*	Median*	Standard Deviation*
Low Susceptibility	75	51.37%	2.223	1.923	1.006
High Susceptibility	71	48.63%			

** of Motion Sickness Susceptibility, Scale Values 1–7*

in *H1: Users who are more susceptible to motion sickness in everyday life show stronger motion sickness symptoms after testing.* Here, H1 is confirmed as there is a significant correlation between motion sickness experienced in everyday life measured by questionnaire 1 (see Table 3) and motion sickness symptoms after VR testing measured by questionnaire 2 (see Table 4)(Pearson correlation = .655; Sig. 2-sided <0.01). A comparison of means of motion sickness symptoms after VR testing with grouping by susceptibility type illustrates the relationship graphically (see Fig. 3). A t-test also confirms significance considering all symptom categories (see Table 7). A regression analysis reveals that 42.5% of motion sickness symptoms can be explained by motion sickness susceptibility (Table 8). The constancy of this influence is illustrated by including the additional variables `age` and `gender` (Table 9).

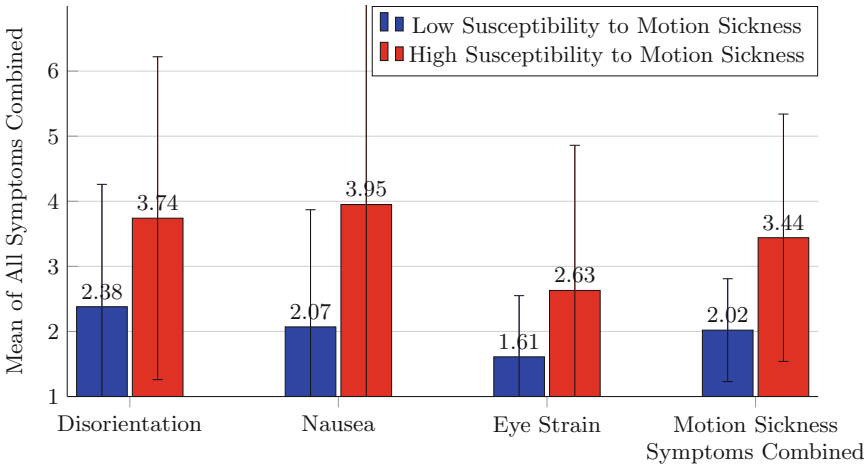

Fig. 3. Mean Comparison including Variance by Motion Sickness Symptoms and Motion Sickness Susceptibility Type

Table 7. t-Test of Independent Samples of Susceptibility Type and Motion Sickness Symptoms

		Levene-Test				
		F	Sig.	T	df	Sig.(2-sided)
Disorientation	Same Variances	4.554	.035	−5.631	144	<.001
	Different Variances			−5.618	139.01	<.001
Nausea	Same Variances	15.872	.000	−6.849	144	<.001
	Different Variances			−6,821	130.624	<.001
Eye Strain	Same Variances	24.625	.000	−4.739	144	<.001
	Different Variances			−4.711	118.917	<.001
Motion Sickness	Same Variances	24.431	.000	−6.983	144	<.001
Symptoms Combined	Different Variances			−6.945	122.404	<.001

Table 8. Regression Analysis of Effect `Motion Sickness Susceptibility` on `Motion Sickness Symptoms Combined`

R	R^2	Corrected R^2	Standard Error of the Subject
.655*	.429	.425	1.408

**influencing Variables; (Constants), Susceptibility*

Table 9. Regression Analysis with Additional Coefficients `Age` and `Gender`

Model	not standardized		standardized		
	Regression Coefficient B	Standard Error	Beta	T	Sig.
Constant	1.7566	.838		2.108	.037
Susceptibility	.873	.095	.623	9.235	<.001
Gender	−.269	.194	−0.94	−1.387	.168
Age	−.022	.032	−.043	−.673	.502

**Dependent Variable: Motion Sickness Symptoms Combined*

5.3 Influence of Resolution on Motion Sickness

Hypothesis *H2* hypothesizes lower motion sickness symptoms are experienced when the resolution quality of the VR stimulus is higher (Condition A – High Resolution) than when the resolution quality is poor (Condition B – Low Resolution). Considering the mean values for verification, the predicted tendency emerges (Fig. 4). The effect differs in the individual symptom categories (disorientation, nausea, eye strain). However, significant results are only recorded for the motion sickness symptom *Nausea* (see Table 10). Although the predicted tendency is fulfilled, hypothesis *H2* can, thus, only be partially confirmed.

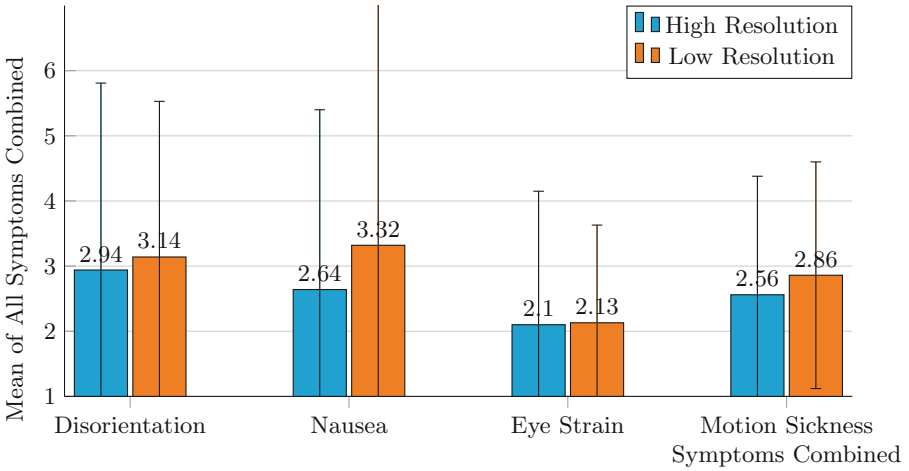

Fig. 4. Mean Comparison including Variance by Motion Sickness Symptoms and Test Condition

Table 10. Indep. Samples t-Test of Test Conditions and Motion Sickness Sympt.

		Levene-Test				
		F	Sig	T	df	Sig.(2-sided)
Disorientation	Same Variances	1.385	.241	−0.761	144	.448
	Different Variances			−0.76	142.01	.448
Nausea	Same Variances	5.567	.019	−2.264	144	.025
	Different Variances			−2.269	141.568	.025
Eye Strain	Same Variances	0.119	.731	−0.152	144	.879
	Different Variances			−0.152	139.448	.880
Motion Sickness	Same Variances	0.108	.672	−1.339	144	.183
Symptoms Combined	Different Variances			−1.339	143.875	.183

The combined influence of test condition (low vs. high resolution) and motion sickness susceptibility type (low vs. high susceptibility), as well as the ranking,

hypothesized in *H3*, is first tested by a comparison of means (see Fig. 5). The hypothesis, which assumes a greater influence of the motion sickness susceptibility type (high/low susceptibility) than that of the resolution quality (high/low resolution), thus can be provisionally confirmed based on this comparison. Ranking by type of susceptibility (low/high susceptibility) in the first instance, followed by test condition (low/high resolution) in the second instance, also occurs at the symptom level. A one-factor analysis of variance (ANOVA) demonstrates the significant differences between the experimental groups (see Table 11), thus confirming hypotheses H3a–d.

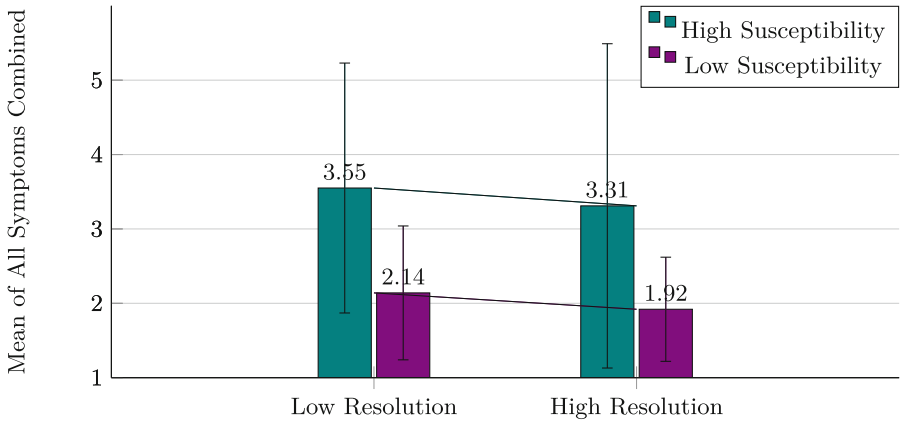

Fig. 5. Mean Comparison including Variance of Motion Sickness Symptoms split by Test Condition and Motion Sickness Susceptibility Type

Table 11. One-Factorial ANOVA of Test Groups and 'Motion Sickness Symptoms Combined'

	Sum of Squares	df	Means of Squares	F	Significance
Between Groups	71.796	3	23.932	16.556	<.001
Within Groups	205.263	142	1.446		
Combined	277.059	145			

**Dependent Variable: Motion Sickness Symptoms Combined*

When the influence of the factors test conditions `High Resolution/Low Resolution` and the motion sickness susceptibility types `Low Motion Sickness Susceptibility/Low Motion Sickness Susceptibility` on the dependent variable 'Motion Sickness Symptoms Combined' is tested in a two-factor ANOVA, it is shown that only the susceptibility type lead to a significant effect (see Table 12). The effect of resolution quality is measurable but not statistically

significant, with a significance level of .293. In summary, the results confirm the hypotheses' presumed trends. However, significant results are for the most part limited to motion sickness susceptibility type and not resolution quality.

6 Discussion and Implications

6.1 Effect of Personal vs. Technical Aspects in the Adoption of VR

The results from our study confirm hypothesis (H1) that real-world motion sickness susceptibility plays a major role in the experience of cybersickness in VR applications. Hypothesis H2, expecting that users who experience VR in high resolution will exhibit lower motion sickness symptoms than users who experience VR in lower resolution, can only be partially confirmed for the motion sickness symptom Nausea. The results show that the role of technical software advancements, such as the enhancement of resolution, does not necessarily solve the problem of cybersickness if the person is already susceptible in the real world. This poses a challenge for the wide adoption of VR and its seamless integration into our everyday life. This finding also raises ethical concerns about whether some user groups would be excluded from the Metaverse.

Table 12. Effects of Test Condition and Motion Sickness Susceptibility Type on 'Motion Sickness Symptoms Combined'

Source	Squared Sum of Type III	df	Means of Squares	F	Sig.	η_p^2
Corrected Model	71.796	3	23.932	16.556	<.001	.259
Constant Term	1075.277	1	1075.277	743.871	<.001	.840
Susceptibility Type	68.360	1	68.360	47.291	<.001	.250
Test Condition	1.610	1	1.610	1.114	<.001	.008
Susceptibility Type* Condition	0.091	1	0.091	0.063	.803	<.001
Error	205.263	142	1.446			
Combined	1350.238	146				
Corrected Overall Variation	277.059	145				

*R^2 = .259($corrected$ R^2 = .243)

Our study is only a first step towards unraveling this interplay between personal and technical factors that may affect the adoption of VR experiences. Future research should continue considering and exploring the effect of personal aspects and how these effects can be mitigated, for example by training or even by medical interventions. Here, providers might learn from other disciplines, for example, the training of astronauts undergoing Autogenic-Feedback Training Exercises that mitigate the effects of motion sickness [56].

6.2 Factors to Consider During VR Experiment Setups

When selecting a test group for a VR study that relates to motion sickness, it is recommended to subject the potential participants to a motion sickness questionnaire (e.g., CSSQ [15]) beforehand, since a significant correlation between motion

sickness in everyday life and motion sickness in VR could be observed. Through this prior test, the sampled group can be adjusted subsequently, depending on whether the study and the tested hypothesis need predominantly participants with low or high motion sickness susceptibility. In cases where the main objective is representative results, this approach allows for ensuring that both groups are represented equally within the test group so as to avoid biases.

To reduce motion sickness in general, a VR HMD with the best possible display resolution should be selected. This is especially recommended for applications known or expected to trigger nausea, as our results have shown. For the implementation of a VR application, it is also recommended to choose a VR HMD with the highest possible resolution, since motion sickness and nausea, in particular, can be reduced in coordination with a suitable application. Additionally, if part of the research goal is to intentionally trigger motion sickness symptoms, it is possible to artificially reduce the resolution via software, so that the experience resembles that of a low-resolution VR HMD.

7 Conclusion and Outlook

As expected and confirmed in previous studies, individual personal factors related to motion sickness susceptibility are valid predictors. Significant associations between motion sickness symptoms and self-assessed motion sickness susceptibility have been consistently demonstrated. In contrast, the effect of resolution quality, while smaller than speculated, offers promising insights for future research in VR eyewear. A significant relationship between resolution quality and the motion sickness symptom *nausea* was demonstrated. Nausea represents only a part of the possible motion sickness symptoms.

Consequences for the use of VR glasses could nevertheless be crucial. As examined in the study by Somrak et al. [50], there is a significant relationship between motion sickness symptoms and user experience with VR headsets. In the present study, a correlation between nausea and the hedonistic benefits of the VR experience also emerged. Obviously, there is an assumption that individuals who develop motion sickness symptoms while wearing VR goggles might derive a lower entertainment benefit from the experience. Analysis of the results suggests that resolution quality alone could only address this issue to a small degree.

The VR industry is continuously striving for new, higher-resolution screens and experiences. It is also questionable whether continuously increasing resolutions will have the same impact on motion sickness symptoms, especially since the human eye can only detect resolution differences to a certain degree [61]. Therefore, future studies could investigate the influence of resolution quality in higher resolution areas and diversify the age and occupational groups. The phenomenon of motion sickness remains multifaceted. For the success and mass suitability of VR glasses, it is nevertheless indispensable to identify as many motion sickness-triggering factors as possible and to provide possible mitigation.

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