Reducing Virtual Reality Sickness for Cyclists in VR Bicycle Simulators

Andrii Matviienko
matviienko@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

Florian Müller
florian.mueller@ifi.lmu.de
LMU Munich
Munich, Germany

Marcel Zickler
Lisa Gasche
Technical University of Darmstadt
Darmstadt, Germany

Julia Abels
Till Steinert
Technical University of Darmstadt
Darmstadt, Germany

Max Mühlhäuser
max@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

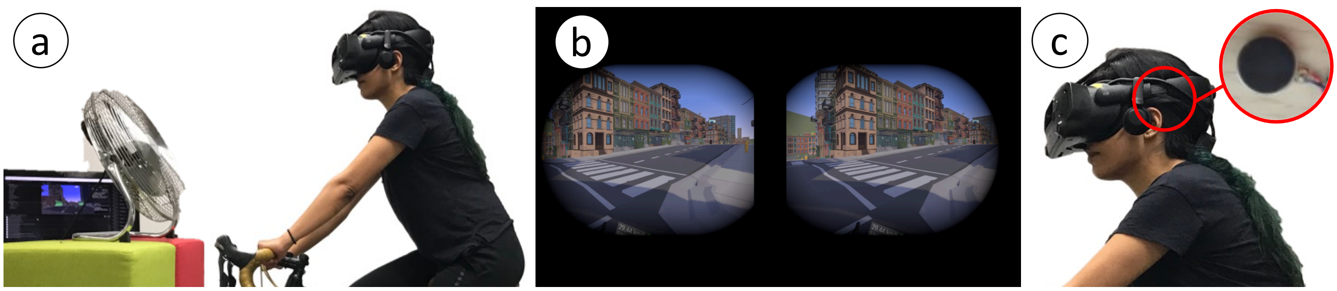

Figure 1: Overview of countermeasures to reduce VR sickness in bicycle simulators: (a) airflow, (b) dynamic field-of-view restriction (FoV), (c) two-sided head-mounted vibrotactile feedback. Airflow creates a wind-like sensation, FoV dynamically restricts the peripheral vision of cyclists by blacking out the field-of-view, and vibration conveys a simultaneous sensation on both sides of the head.

ABSTRACT

Virtual Reality (VR) bicycle simulations aim to recreate the feeling of riding a bicycle and are commonly used in many application areas. However, current solutions still create mismatches between the visuals and physical movement, which causes VR sickness and diminishes the cycling experience. To reduce VR sickness in bicycle simulators, we conducted two controlled lab experiments addressing two main causes of VR sickness: (1) steering methods and (2) cycling trajectory. In the first experiment (N = 18) we compared handlebar, HMD, and upper-body steering methods. In the second experiment (N = 24) we explored three types of movement in VR (1D, 2D, and 3D trajectories) and three countermeasures (airflow, vibration, and dynamic Field-of-View) to reduce VR sickness. We found that handlebar steering leads to the lowest VR sickness without decreasing cycling performance and airflow suggests to be the most promising method to reduce VR sickness for all three types of trajectories.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Empirical studies in HCI**.

KEYWORDS

virtual reality, cycling, VR sickness, bicycle simulators

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1 INTRODUCTION

Bicycle simulators are increasingly useful in many application areas, such as health [58], entertainment [1] [22] and research [36–38], where they facilitate prevention of cardiovascular diseases, improve physical conditions using gamification [3, 22, 58], and provide an evaluation platform for researchers in safe laboratory conditions [62]. Most of these bicycle simulators [6, 32, 34, 54, 62, 64, 73] are placed on stationary platforms and employ virtual reality (VR) technology to present a virtual world to users through an immersive 3D experience and a resulting high sense of presence [17, 55]. However, due to a mismatch between visual feedback provided by a

[1] https://virzoom.com, https://www.vzfit.com/

simulation and a physical movement in the space while cycling [41], users often experience virtual reality (VR) sickness, which leads to a decreased cycling performance [28] or even dropouts from experiments [13, 14, 65].

Although we cannot avoid the aforementioned mismatch between visual perception and physical movement in VR bicycle simulators, we can influence factors that can reduce VR sickness. These factors include (1) hardware which determines the quality of VR (e.g., display type, hardware Field-of-View, latency), (2) VR content responsible for the degree of VR fidelity and sickness (e.g., optical flow, reference frame, controllability), and (3) human factors (e.g., age, gender, prior VR experience) [10]. Given that the hardware-related aspects from the first category will most likely improve with time and we have no control over interpersonal differences related to the third category, we explore the aspects related to human perception from the second category related to VR fidelity and sickness. In the case of VR bicycle simulators, these factors are typically influenced by: (1) rotational movements (*steering*) that increase a mismatch between the visual and vestibular systems and (2) the effect of optical flow when moving through space along different axes, e.g., cycling straight, with turns and with slopes (*moving through space*). Therefore, our work aims to reduce VR sickness for cyclists in VR bicycle simulators by exploring the effects of steering and movement through space while maintaining a high cycling performance. The latter implies that VR sickness countermeasures do not come at the cost of a decreased cycling experience and performance in terms of speed and accuracy.

In the first experiment, we investigated three bicycle steering methods based on three types of control via (1) the conventional rotation of a handlebar, (2) head rotation, and (3) a close-to-reality leaning of an upper body, and their influence on the VR sickness in bicycle simulators. We discovered that steering via rotation of the handlebar leads to the lowest VR sickness, higher steering accuracy and usability. In the second study, we employed the handlebar steering method and explored an airflow, a dynamic restriction for the field-of-View, and head-mounted vibrotactile feedback (Figure 1) to reduce VR sickness under three types of movement through space: (1) cycling on a straight line, (2) with turns, and (3) with slopes. We found that airflow is the most efficient countermeasure for all types of movement in terms of VR sickness reduction and cycling realism based on subjective measures.

Our main research contributions include:

- An empirical evaluation of three bicycle steering methods and their influence on the VR sickness.
- An empirical evaluation of three countermeasures to reduce VR sickness in VR bicycle simulators while cycling straight, with turns, and with slopes.

2 RELATED WORK

In this section, we provide an overview of bicycle simulators, their steering methods, VR sickness, and countermeasures of its mitigation.

2.1 Bicycle Simulators

Although cycling in stationary bicycle simulators is tangentially approaching real cycling experience [47], they continue to play an important role in health [58], entertainment [22] and research [36–38]. In particular, bicycle simulators are crucial in the research as a cost-effective evaluation method with cyclists as vulnerable road users [5, 42]. Their advantage lies in the control over experiments, environmental consistency [18, 40], and more importantly a simulation of potentially dangerous traffic situations without causing harm for participants and other road users [18, 52]. However, despite several benefits of using bicycle simulators, it is important to maintain a high correspondence between the real world and a simulation, to produce valid results [23, 61].

To facilitate a high correspondence between the reality and simulation while cycling, many researchers used virtual reality (VR) technology [6, 9, 24, 32, 34, 47, 54, 62, 64, 73] to ensure a high level of presence and immersion in the simulated environment. In this way, researchers aim to bring the simulated environment a step closer to reality. For example, O'Hern et al. [9, 47] discovered that there are no significant differences between the real world and VR regarding lane position, deviation in lane position, passing distance, speed reduction at intersections, and several aspects of head movements. However, participants were riding significantly slower in VR. Another example of earlier bicycle simulators – Peloton Bicycling Simulator [9] – was designed to facilitate exercising at home in a virtual world. The setup is very similar to today's home exercise software, e.g., Zwift [2], which consists of a bicycle, attached to a bicycle trainer, a PC, and a fan. Other existing bicycle simulators use similar principles, differing in the type of displays, the use of sensors or actuators [24, 32, 64, 73]. However, despite the existing advances in mimicking cycling in VR bicycle simulators, there is no clear design decision regarding the most efficient steering method and countermeasures to reduce VR sickness imposed by the mismatch between the visual and physical sensations. This leads to two questions: (1) *which steering method is the most appropriate for bicycle simulator* and (2) *which steering method induces the lowest VR sickness*. We outline the state-of-the-art regarding both of these questions in the following subsections.

2.2 Steering in Bicycle Simulators

Steering in bicycle simulators plays undoubtedly an essential role in indicating a direction of movement. Researchers have implemented several steering methods via rotation of the handlebar (with and without a turntable), buttons, or leaning of a cyclist. Steering with a handlebar rotation is typically implemented via a free movement of the handlebar with the front wheel on a floor [32, 54] or turntable [62], or without a front wheel, but a fork fixed in front and a movable handlebar [36–38]. Another example by Katsigiannis et al. [24] shows steering using buttons attached to both sides of the handlebar. In all these cases rotation of the handlebar in the horizontal plane is reflected in the simulator, i.e., turning a handlebar 10° to the left will rotate the camera view of the simulation for the same angle. Therefore, we used a handlebar steering method as a conventional way of steering in many bicycle simulators.

Leaning of the upper-body to indicate a direction of movement is the common method used for cycling in the real world [39]. Although some projects used a Kinect tracking of the body movements

[2] https://www.zwift.com

in bicycle simulators [3], to our knowledge, it was not empirically investigated in the previous work. Therefore, in this paper, we look closely at the performance of the handlebar and leaning steering methods in terms of VR sickness, accuracy, and usability. Additionally, we explore a steering method based on the head movement in car simulators, inspired by the work of Saito et al. [53]. They identified horizontal direction, yaw rotation, and roll rotation as potential candidates for effective steering based on head movement, i.e., you drive where you look. Their results showed that the horizontal axis movement is the most reliable, reduces VR sickness, and increases usability and realistic motion. In this paper, we explore the possibilities of this idea applied to bicycle simulators and its influence on VR sickness and usability. We focus, however, on the body-based steering movements due to their natural interaction, i.e., the upper-body, and previously shown promising results for the handlebar [36, 38].

2.3 Virtual Reality Sickness and Corresponding Mitigation

Virtual reality (VR) sickness [33], cybersickness [48], often called Visually-Induced Motion Sickness (VIMS) [8], or simulator sickness [13] describes a set of symptoms such as nausea, headache, general discomfort, and sweating, experienced during and after exposure to a virtual environment. These terms are often used interchangeably, therefore, in this paper, we refer to the aforementioned symptoms as a Virtual Reality (VR) sickness. VR sickness is a common issue in the VR environments caused by a sensory conflict induced by the disparity in motion between two sensory systems – visual and the vestibular [27]. This motivated researchers to explore the ways of reducing VR sickness [11, 30, 50, 57] by employing two main approaches focused on the two aforementioned sensory systems: (1) visuo-vestibular and (2) visual modification.

The visuo-vestibular approaches employ physical stimulation around the vestibular system. Some of the examples include galvanic feedback [20, 35, 67], airflow [14, 21], bone-conductive vibration [66, 67], vibration on a seat [14], head [49], and feet [29, 60] to enhance participants' sensation of self-motion. Although galvanic feedback is a successful countermeasure against VR sickness [20, 35, 67], it is not recommended for some populations, e.g., pacemaker users, women in pregnancy, and can produce symptoms of discomfort in healthy users [31, 67]. Another approach employs bone-conducted vibrations with an audible frequency of 500Hz behind the ears [66, 67]. However, previous work has shown that frequencies above 150Hz are perceived as annoying, uncomfortable, and obtrusive [25, 43–45], which motivates our work to find more unobtrusive and comfortable methods. Airflow and vibration, on the other hand, have been successful in reducing VR sickness in simulations without causing much discomfort. For example, D'Amour et al. [14] have shown that continuous airflow at a fixed speed placed in front of participants significantly reduced cybersickness compared to vibration in the chair. In another paper, Harrington et al. [21] investigated the effect of a desk fan while driving a car in a virtual environment and found that the airflow had significantly reduced participants' cybersickness. As for the head-mounted vibration, Peng et al. [49] explored this idea to reduce VR sickness while walking in VR using a frequency of 150Hz of the vibration. Their results showed that 2-sided head-mounted vibration is effective in reducing VR sickness and discomfort, which significantly improved the realism of VR walking. Therefore, in this paper, we explore both airflow and head-mounted vibrotactile feedback to reduce VR sickness in bicycle simulators, as they have been successful in previous work.

The visual approach aims to visually modify the perception of VR environments from the user's point of view. Successful examples for the visual approach, e.g., blurring, vignette, blink, are widely used for teleportation in VR, but often diminish presence in realistic environments [16, 51, 63]. A reference frame is another example of visual modifications applied directly to the user's view to enhance spatial and motion judgments, e.g., with a virtual nose [68, 69]. However, the reference frames occlude virtual scenes and remain static concerning the user's head motion [69], without accounting for changes in the virtual environment. Another common method to reduce VR sickness is to restrict the Field-Of-View (FoV), as a larger FoV can increase VR sickness due to visual flux in motion perceived in the peripheral view.

Therefore, reducing the FoV either statically [7, 56] or dynamically [15, 33, 59, 71] can reduce VR sickness. While static FoV restriction is applied for the entire duration of the experience, the dynamic FoV restriction is applied on-demand in situations that might cause vection and thus VR sickness, e.g., (angular) accelerations. The latter approach is also mentioned in the best practice recommendations of Oculus [4] and used in commercially available games (e.g., Sniper Elite VR [5]) and experiences [1, 59]. Therefore, in this paper, we also explored a dynamic FoV restriction as one of the methods to reduce VR sickness in the VR bicycle simulators. In the following, we describe two studies that focus on exploring steering methods and countermeasures to reduce VR sickness in VR bicycle simulators.

3 STUDY 1: STEERING METHODS

In the first study, we investigated the influence of three bicycle steering methods on the VR sickness of cyclists in virtual reality bicycle simulators. Therefore, for this experiment we had the following research question: *Which steering method is the most suitable for VR bicycle simulators in terms of VR sickness and cycling performance?*

3.1 Participants

We recruited 18 participants (11 male, 7 female) aged between 22 and 34 years old (M = 26.2, SD = 2.9) via university mailing lists, social media, and word of mouth. Four participants cycle daily, six ride at least once a week, five once a month and the remaining three cycle less than once a month. Thirteen participants had no experience with VR. All participants had normal or corrected-to-normal vision. Participants were compensated with snacks and drinks for their time.

3.2 Study design

The study was designed to be within-subject with *steering method* as the independent variable. The experiment consisted of three

[3] http://spinnulators.github.io/Spinnulator/

[4] https://developer.oculus.com/resources/locomotion-design-reduce-optic-flow/

[5] https://rebellion.com/games/sniper-elite-vr/

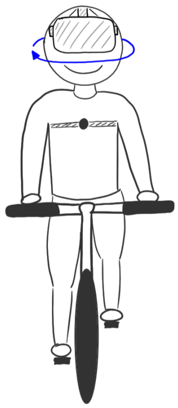

Figure 2: In the first study, we evaluated three steering methods based on the: (1) Head-Mounted Display (HMD) (left), (2) handlebar (center), and (3) upper-body (right). The HMD method allows steering by turnings one's head left and right, the handlebar – by turning the handlebar, and the upper-body – by leaning left and right.

experimental conditions, which included cycling in the virtual environment on the bicycle simulator with (1) handlebar, (2) HMD, and (3) upper-body steering methods (Figure 2). While the handlebar is a conventional method for many bicycle simulators and leaning of the upper body is a way to steer a bicycle in the real world, we included a promising method based on the previous research for steering in cars using a head rotation. With these three methods we aimed not only to explore existing steering methods in bicycle simulators and the real life, but also to assess levels of control with different parts of body: (1) hands – handlebar, (2) head – HMD, and (3) upper body – leaning. The order of the steering methods was counterbalanced using a balanced Latin square. Every route had an equal length of 1.4 km with five left and five right turns each. Except for the changes in the road trajectory, all routes contained two slalom parts with obstacles to enforce steering with smaller rotation angles when switching lanes (Figure 3). To investigate the accuracy of the steering methods, we placed coins equidistant from each other along a predefined path and instructed participants to collect as many coins as possible. Every steering method was randomly assigned to a cycling route and participants' task was to cycle this route following arrow indicators presented in the simulation and collect the coins placed on the road along the predefined trajectory.

3.3 Apparatus

We conducted the experiment in the developed virtual reality (VR) bicycle simulator, which consisted of the bicycle (28-inch wheel) placed on the fixed platform with lateral suspension (Kinetic Rock and Roll[6]). Cycling actions, such as steering, pedaling and braking, were reflected in the simulation shown in the VR head-mounted display. The VR environment was implemented using Unity SDK (2020.1.12f1) and SteamVR assets and consisted of the virtual city in the flat landscape. The bicycle was fitted with a Garmin Speed

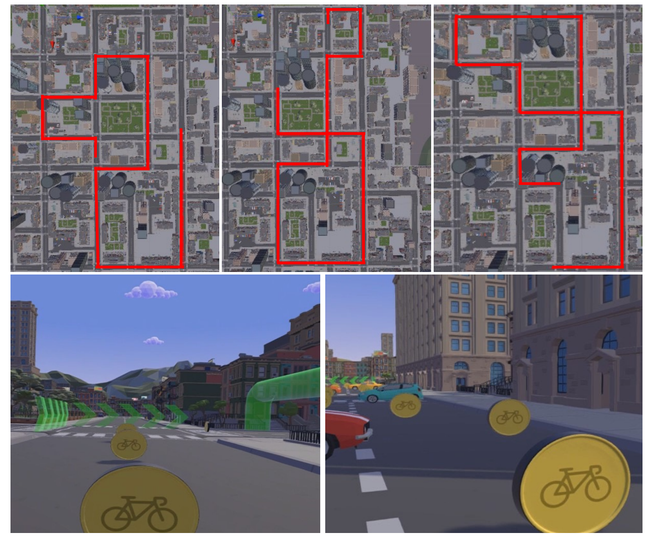

Figure 3: In the first study, we investigated three routes (bird's eye view above), where each route consisted of five left and right turns and contained coins placed at equal distances from each other. We also added two slalom tracks with obstacles to enforce steering with smaller turning angles compared to larger turning angles for 90°turns (bottom).

Sensor 2 on the rear wheel, which transmits real-time speed via ANT+ and Bluetooth to the simulation (Figure 4).

As for the *handlebar steering* method, we placed one VR tracker on the front wheel to measure a rotation angle of the handlebar and the second on the bicycle platform for calibration using 3D-printed brackets. With the help of the trackers, the setup could be oriented arbitrarily in the room while still having the correct orientation of the virtual bike when starting the simulation. The front wheel of the bicycle was placed on a turntable to facilitate stable rotation of the handlebar. The *HMD steering* method was implemented using the orientation of the VIVE headset (angle tracking error <0.02° [46]) to capture the head's yaw rotation. Finally, the *upper-body steering* was enabled via the tilting of the bicycle platform to left and right sides similar to cycling on a bicycle in the real world. For tracking the upper-body, we placed a polar H10 sensor with a gyroscope on participants' chest to measure the body rotation and converted it into a steering angle.

3.4 Measurements

To investigate the performance of the bicycle steering methods and their influence on the VR sickness, we measured the following dependent variables:

- *Virtual Reality Sickness*: for every condition, participants filled in the questions from the Simulation Sickness Questionnaire (SSQ) to assess their general state after cycling. To estimate participants' VR sickness during cycling we used Fast Motion Sickness (FMS) Scale, which included a question with a scale from 0 ("I feel perfectly fine") to 20 ("I want to quit the task, because I feel very bad") and was asked every

[6]https://www.kurtkinetic.com/trainers-products/rock-and-roll-smart-2

Figure 4: Experimental setup used in both studies: Participants cycled on a stationary bicycle simulator while wearing a VR head-mounted display. The VR trackers and the turntable were used to measure the rotation angle of the handlebar and speed sensor – the cycling speed. In the second study, additional countermeasures against VR sickness were used: a fan placed in front of the head, vibrotactile feedback integrated into the head-mounted display behind the ears, and a reduction in the field of view displayed in the HMD. Another difference between study 1 and 2 is in the bike platforms: The figure shows the Tacx platform used in Study 2, while Study 1 used the Kinetic Rock and Roll to facilitate upper body movements.

30 seconds. To calculate the SSQ score [26], we used the formula from [4].

- *Cycling accuracy*: for every condition, we counted the percentage of coins participants collected on the road while cycling with a steering method.
- *Usability of the steering methods*: for every condition, participants filled a System Usability Score scale to estimate the usability of a steering method.
- *Task Completion Time*: for every, condition we measured the time it took participant to finish the route.
- *Number of collisions*: for every condition, we counted the number of times participants cycled into a virtual object in the simulation.
- *Subjective pleasantness and accuracy*: for every condition, we asked participants to assess how pleasant and how accurate they found a steering method using a 5-point scale (1 – very unpleasant/imprecise, 5 – very pleasant/precise).

3.5 Procedure

For our study we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic. All testing equipment was disinfected and the hall used was aired out for a minimum of one hour between participants. After obtaining informed consent, we collected participants' demographic data. Afterwards we provided a brief overview of the procedures, which included explanations of the steering methods and a test ride in the simulator. They started cycling when they felt comfortable. Participants' task was to cycle in the simulation, follow the navigation arrows placed in the environment and collect coins on the way. At the end of the study, we interviewed the participants about their preferences and problems experienced with the steering methods. The entire study lasted approximately one and half hours.

3.6 Results

We found that the handlebar steering method leads to the lowest VR sickness and the lowest number of collisions. Moreover, it has the highest usability and steering accuracy compared to HMD and upper-body steering methods in virtual reality bicycle simulators. We used the Friedman test and Wilcoxon-signed rank test for post-hoc analysis of the non-parametric data. For pairwise comparisons, we used a Bonferroni correction. We outline these findings in detail in the following.

3.6.1 VR Sickness. We found that handlebar steering has the lowest SSQ-value ($M = 80.8, SD = 74.7$) and therefore leads to lower VR sickness, followed by a steering via HMD ($M = 90.8, SD = 70.6$) and upper-body ($M = 169, SD = 107$). These differences between

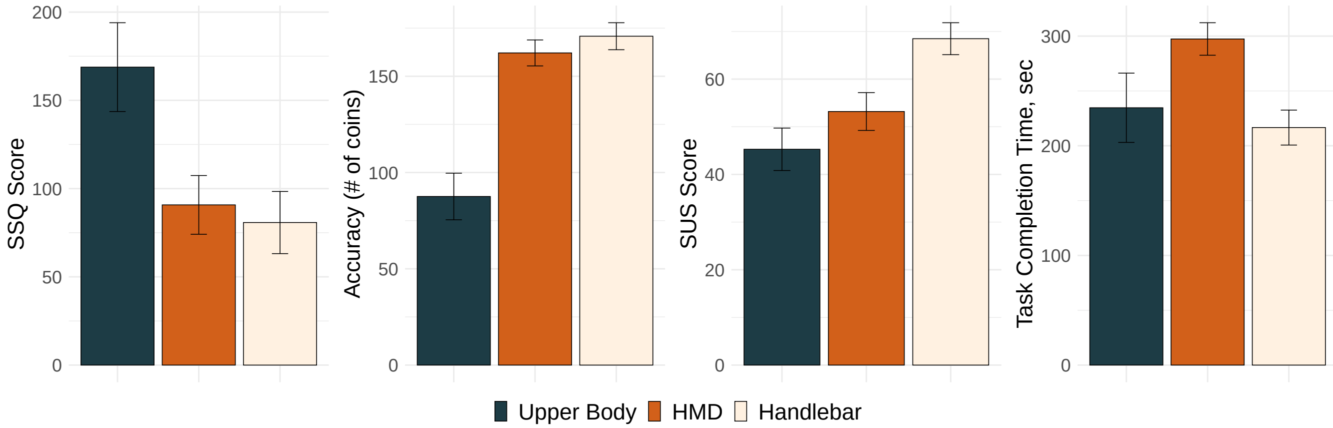

Figure 5: Overview of results: means and standard errors for Simulation Sickness Questionnaire (SSQ) score, accuracy as a number of collected coins, System Usability Score and task completion time.

the steering methods were statistically significant according to the Friedman test ($\chi^2(2) = 18.85, p < 0.001, \eta^2 = 0.52$). The pairwise comparisons showed that upper-body steering method had a statistically significant higher SSQ value compared to the handlebar ($p < 0.001$) and HMD ($p < 0.001$) methods. Moreover, the SSQ score was significantly higher using the HMD steering than the handlebar ($p < 0.001$). As for the Fast Motion Sickness (FMS), we discovered that the upper-body method induces higher FMS score (average score over time) ($M = 4.91, SD = 3.47$) than the HMD ($M = 3.57, SD = 3.9$) and the handlebar ($M = 3.26, SD = 2.67$). These differences were statistically significant ($\chi^2(2) = 9.2, p < 0.001, \eta^2 = 0.26$). The pairwise post-hoc tests showed that the upper-body had a statistically higher FMS score compared to the HMD ($p < 0.001$) and handlebar ($p < 0.001$), but not between the handlebar and the HMD ($p > 0.05$) (Figure 5 left).

3.6.2 Cycling accuracy. We found that the handlebar steering was the most accurate with 96.21% ($M = 170, SD = 30$) accuracy rate, followed by HMD steering with 88.04% ($M = 162, SD = 29$) and upper-body with 56.52% ($M = 88, SD = 51$). These differences between the steering techniques were statistically significant ($\chi^2(2) = 25.4, p < 0.001, \eta^2 = 0.7$) and the pairwise comparisons showed that the upper-body steering was less accurate than the handlebar ($p < 0.001$) and the HMD ($p < 0.001$) steering methods. Moreover, participants were significantly more accurate with the handlebar steering than with HMD ($p < 0.01$). This finding was further supported by the subjective feedback, which showed that the handlebar steering was perceived as the most accurate ($M = 4.5, SD = 0.62$), followed by HMD ($M = 3.78, SD = 0.94$) and upper-body steering ($M = 2.33, SD = 1.1$). The Friedman test showed that the differences between the steering methods are statistically significant ($\chi^2(2) = 25.7, p < 0.001, \eta^2 = 0.71$). The pairwise comparisons have shown that the handlebar steering was perceived as the most accurate method compared to HMD ($p < 0.001$) and upper-body ($p < 0.001$). HMD steering was also perceived as more accurate than with upper-body ($p < 0.001$) (Figure 5 middle left).

3.6.3 Task completion time. We found that with the handlebar steering it took participants the shortest amount of time to finish the route ($M = 217s, SD = 68$), followed by the upper-body ($M = 235s, SD = 134$) and the HMD ($M = 297s, SD = 63$) methods. Using the Friedman test we revealed that this difference was statistically significant ($\chi^2(2) = 12.3, p < 0.01, \eta^2 = 0.34$). The pairwise comparisons have shown that steering with the handlebar was faster compared to the steering with the HMD ($p < 0.001$) and the upper-body ($p < 0.001$). Moreover, cycling with the upper-body method led to a shorter task completion time than with the HMD ($p < 0.001$) (Figure 5 right).

3.6.4 Number of collisions. We found that with the handlebar steering method participants had zero collisions compared to the HMD ($M = 0.33, SD = 1.03$) and the upper-body ($M = 0.94, SD = 1.47$) steering methods. The Friedman test has shown a statistically significant difference for the number of collisions ($\chi^2(2) = 9.9, p =< 0.01, \eta^2 = 0.28$). The pairwise comparisons have shown a significantly higher number of collisions with the upper-body compared to the handlebar ($p < 0.001$) and the HMD ($p < 0.001$). However, we did not observe statistically significant differences between the HMD and the handlebar steering methods ($p > 0.05$).

3.6.5 Usability. We found that the the handlebar steering has the highest usability ($M = 68.5, SD = 14$) compared to HMD ($M = 53, SD = 17$) and upper-body ($M = 45, SD = 19$) methods, which was shown by statistically significant differences for usability ($\chi^2(2) = 11.5, p < 0.01, \eta^2 = 0.32$) using the Friedman test. The pairwise comparisons showed that the handlebar method has a significant higher usability than HMD ($p < 0.001$) and upper-body ($p < 0.001$) methods. However, we did not find statistically significant differences between HMD and upper-body methods ($p > 0.05$) (Figure 5 middle right).

3.6.6 Problems and preferences. Concerning participants' preferences for steering methods, we found that the majority preferred steering with the handlebar (n=13), followed by HMD (n=5). None of the participants ranked steering with the upper-body as the most preferred steering method. The ranking also correlates with how pleasant participants found the steering methods with the handlebar having the highest score ($M = 3.83, SD = 1.04$), followed by HMD ($M = 3.39, SD = 1.14$), and the upper-body ($M = 2.11, SD = 0.83$).

The highest preference for the handlebar steering method was expressed by the fact that the participants had a better control over a bicycle, in particular for narrow turns, and it was easy to use it and go in the intended directions. As some of our participants mentioned: *"The handlebar controls were very easy to steer. Even tight corners were easy to drive, the controls responded well."*. [P2, M, 27 years old], *"I could easily go in directions I had to go and I had no problems orienting myself in the environment."* [P7, M, 30 years old]. The main point of critique was a high sensitivity level of the handlebar. For example, P8 (M, 31 years old) noted that it feels: *"Like a bicycle, although here the sensitivity sometimes felt too high."*.

The HMD steering method seems to be a good option for people who rarely cycle on a real bicycle, it was perceived as easy and fun to use. As some of the participants mentioned: *"I think the steering method is interesting and can be put to good use by people who rarely ride a real bike. However, if you are used to steering by hand movement and tilting your upper body, it is very irritating that the simulator does not react to it."* [P2, M, 27 years old], *"Was super fun! Funnily enough, more intuitive than steering with the steering wheel"* [P13, F, 26 years old]. As for the main disadvantages, the participants expressed an inability to observe the environment, the unusual feeling of not using the handlebar at all and lack of a cycling feeling. Some of our participants noted the following: *"It worked out quite well, but I prefer to steer with the handlebar. It was a shame not to be able to look at the landscape."*, *"It was easy to steer and good at cornering. A little unusual not having to use the handlebar."* [P4, F, 24 years old], or *"Difficult because you are used to steering with a handlebar"* [P6, M, 25 years old].

As for the steering with upper-body, participants found it very imprecise, had no good feeling for steering and control, and lacked steering with a handlebar. These findings are supported by the following statements: *"Unfortunately, the steering using the upper body tilt is very imprecise, which makes driving very exhausting."* [P2, M, 27 years old], *"I didn't get a real feel for the steering, no real control, so I felt very insecure."* [P5, F, 26 years old], and *"A bit unintuitive, it might be easier with a fixed handlebar".* [P10, M, 23 years old].

3.7 Discussion

In general, we observed a significant effect of steering on VR sickness in virtual reality bicycle simulators. The upper-body steering (or leaning) method led to a higher motion sickness based on the SSQ scale compared to handlebar and HMD steering methods.

During cycling in the real world the upper-body plays an important role in both balancing and steering. Bicycle balancing is absent in the bicycle simulators and turns into a slightly different experience compared to the real-world. Therefore, our finding can be possibly explained by the lack of an actual physical movement in the bicycle simulator compared to the real-world. Moreover, the HMD steering leads to a lower VR sickness compared to the upper-body method most likely due to the different axis of rotation and a smaller body movement, i.e., head vs. the whole upper-body. These differences were discovered during and after cycling, as shown by the results of FMS. This might imply that the growing level of VR sickness over time leads to VR sickness after a ride. Thus, in terms of VR sickness the handlebar steering method is better applicable in the stationary bicycle simulators.

Our results for the HMD and upper-body steering methods are different from the ones in the car driving setup [53]. They reported no motion sickness for yaw rotation (HMD) and X movement (upper-body steering) and only slight motion sickness for the steering wheel condition. For cycling in VR bicycle simulator, these steering methods differ significantly based on our results. These differences are most likely caused by different steering setups (car driving vs. cycling) and the duration of driving/cycling. Leaning on a bicycle might be more difficult than in a car simulator, since participants' center of mass is higher, and therefore keeping a balance becomes more challenging. This feeling of insecurity could have contributed to an increased motion sickness. As for the duration, while our participants spent about 3-5 minutes in the simulation to cycle 1.4 km, participants in the study by Saito et al. [53] had performed multiple trials each that only lasted a few seconds.

The factors unrelated to VR sickness, such as accuracy, speed and usability, have indicated several differences among the steering methods. Cycling with the handlebar method led to a better accuracy and speed of collecting coins, caused a lower number of collisions with other objects and has a higher usability compared to the HMD and upper-body steering. One of the possible reason for this outcome can lie in the feeling of control over the bicycle in the VR simulation, which is also supported by the results regarding the subjective accuracy with the handlebar. This finding also leads us to the conclusion that participants' upper-body and head-movement, i.e., HMD, facilitates less granular movement compared to hands. The result further supports the assumption that the faster participants reach their goal, the higher control over steering and cycling they have, as shown by the task completion time. Therefore, we decided to use a handlebar steering for the follow-up experiment as a method with a lower VR sickness, higher usability and control, accuracy, speed and the highest rank based on the subjective feedback. With this method we aim to minimize the VR sickness caused by the steering and focus on the types of movement and the effects of countermeasures to reduce the VR sickness.

4 STUDY 2: COUNTERMEASURES AND TYPES OF MOVEMENT

In the second study, we investigated the effect of moving through space along different axes, i.e., cycling straight, with turns and with slopes, and three countermeasures to reduce VR sickness induced by these types of movement.

4.1 Participants

We recruited 24 participants (15 male, 7 female, 2 non-binary) aged between 21 and 34 (M = 26.3, SD = 3.9) via university mailing lists, social media, and word of mouth. None of them have participated in the previous experiment. Ten participants ride a bicycle at least once a week and 15 have already been on a stationary bicycle before. 14 of the subjects had little to no (< 5 hours) experience with virtual reality and 2 had experience of over 100 hours. Seven participants have played games with locomotion in VR. All participants had normal or corrected-to-normal vision. Participants were compensated with snacks and drinks for their time.

4.2 Study design

The study was designed to be within-subject with *countermeasure* and *type of movement* as the independent variables. We explored three *countermeasures*: (1) airflow, (2) dynamic Field-of-View (FoV) restriction, (3) head-mounted vibration, and no measure as a baseline (Figure 1). Given that cycling in VR simulators implies changes in speed and steering, we selected the countermeasures that could dynamically adjust for these changes related to locomotion. Therefore, all three countermeasures linearly depended on two factors: (1) cycling speed and (2) rotation of the handlebar. The higher the speed and/or the larger the rotation angle of the handlebar, the higher is the intensity of the countermeasure, e.g., a higher intensity of the air flow and vibrations, or more restriction of the field-of-view. If the speed and the angle of the handlebar do not change for three seconds, the countermeasures turn off. Moreover, all three countermeasures were chosen based on their success in reducing VR sickness and implemented in accordance with the works about dynamic FoV restriction [15, 33, 59, 71], head-mounted vibration [49], and airflow [14, 21]. As for the *type of movement*, we considered cycling on a straight line (movement along one axis), cycling with turns (movement along two axes), and cycling with slopes (movement along three axes) (Figure 6). With this, we aimed to instigate VR sickness related to different types of locomotion and investigate which countermeasure is the most suitable. Cycling with and with turns included four turns left and four turns right in a random order. The combination of all four levels of countermeasures and three levels of *type of movement* resulted in twelve experimental conditions. The order of the conditions was counterbalanced using a balanced Latin square.

4.3 Apparatus

We conducted the experiment in the developed virtual reality (VR) bicycle simulator as in the first experiment (Figure 4). The only difference in the setup was a stationary platform Tacx, which limits tilting left and right movements. Based on the results from the first experiment, we used a handlebar steering method as the one which induces the lowest VR sickness and has a higher usability, precision and feeling of control. The simulation consisted of the virtual city with flat and hilly parts to facilitate different types of movement, e.g., cycling uphill/downhill, turning left/right. To measure the heart rate and ECG of the cyclists, we asked participants to wear a Polar H10 heart rate sensor throughout the whole study.

4.3.1 Airflow. The air fan (a 220V AC desk fan) was placed 115-125 cm away [7] in front of the participants on the eye level and was directly connected to ESP32 with a TRIAC and an AC Dimmer Module[8] to control the speed of the fan. The ESP controls the fan speed by triggering the TRIAC into conduction for a part of each sine wave cycle depending on the value it is set to. The beginning of each cycle is detected using the zero cross detector.

4.3.2 Dynamic Field-of-View Restriction. The implementation of the Field-of-View Restriction is based on the work of Fernandes and Feiner [15]. However, instead of rendering the texture on a rectangle in front of the camera, it was blitted into the output image using a custom additional render pass added to the URP renderer. Additionally, we introduced another variable to prevent the black outer area for one eye to overlap with the transparent area for the other eye. A custom MonoBehavoir generates a restriction value between 0 and 1 for each frame and adjusts the inner and outer radius variables of the rendered material accordingly. The restriction value is influenced by the current speed, steering angle of the virtual bike and the slope it is currently moving on. For steering angle and slope, the restriction value is linearly interpolated between 0.53 and 0.69.

4.3.3 Head-mounted vibrotactile feedback. For the vibration feedback, we augmented a head strip with three vibration modules connected to a ESP32 microcontroller placed in the 3D-printed box on the back of the head, based on the work by Peng et al. [49]. The vibration motors[9] (diameter = 10 mm, thickness = 2.7 mm) have a rated voltage between 2.5V and 3.8V and rated speed of 11000 ± 3000rpm (133.33 - 233.33 Hz). We controlled the voltage using pulse width modulation (PWM with 256 steps) and Mosfets with the range of values between 100 and 178 and therefore the maximum frequency of 140.89Hz, as suggested by Peng et al. [49] to prevent head discomfort.

4.4 Measures

To investigate the effects of the VR sickness countermeasures and types of movement in virtual reality bicycle simulator, we measured the following dependent variables:

(1) *VR sickness*: we assessed VR sickness qualitatively using Simulator Sickness Questionnaire (SSQ), Fast Motion Sickness (FMS) Scale and Motion sickness susceptibility questionnaire (MSSQ) [19]. After each condition participants were asked to rate their VR sickness using SSQ and during each condition participants were asked to rate their VR sickness every 30 seconds using FMS.
(2) *Cycling performance*: for all conditions, we logged speed, steering angles and position of cyclists in the simulation.
(3) *Perceived presence*: at the end of the study participants assessed the presence in the bicycle simulator using Igroup Presence Questionnaire (IPQ) (a scale from -3 to 3).
(4) *Simulation realism*: at the end of the study, every participant assessed the realism of the virtual reality simulation using a 5-point Likert scale (1 – very unrealistic, 5 – very realistic).

4.5 Procedure

For our study we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic. All testing equipment was disinfected and the hall used was aired out for a minimum of one hour between participants. After obtaining informed consent, we collected participants' demographic data. Afterwards we provided a brief overview of the procedures, which

[7]We provide a range of distances here, since it varied depending on the participants' height and head movements while cycling.
[8]https://robotdyn.com/ac-light-dimmer-module-1-channel-3-3v-5v-logic-ac-50-60hz-220v-110v.html
[9]https://cdn-shop.adafruit.com/product-files/1201/P1012_datasheet.pdf

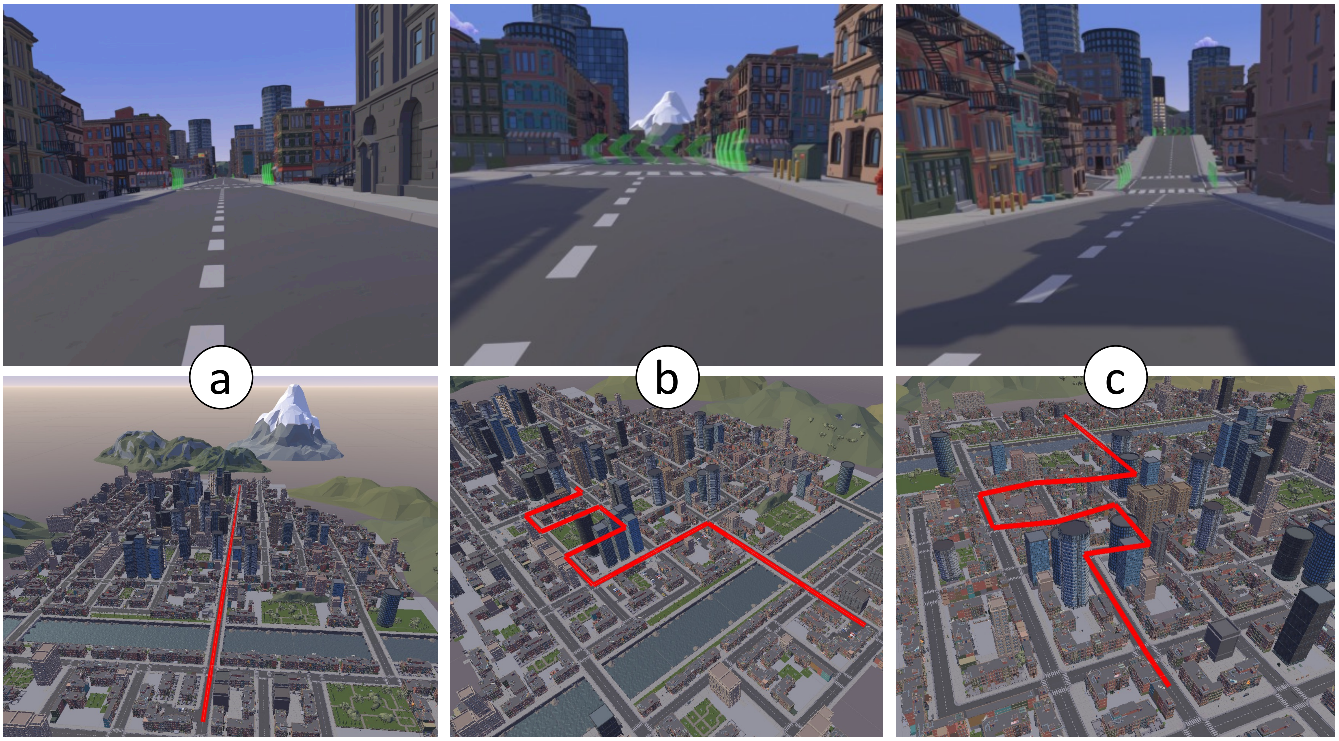

Figure 6: Routes explored in the second study from a first person perspective (above) and bird's-eye view (below): (a) 1D trajectory (cycling straight), (b) 2D trajectory with turns left and right (turns), and (c) 3D trajectory with turns left/right and slopes up/down (slopes).

included explanations of the VR sickness countermeasures and a test ride in the simulator. To estimate participants' existing level of VR sickness before the experiment they were asked to fill Motion Sickness Susceptibility questionnaire and Simulator Sickness Questionnaire (SSQ) as a baseline. They started cycling when they felt comfortable. Similar to the first experiment, participants' task was to cycle in the simulation and follow the navigation arrows placed in the environment. At the end of the study, we interviewed the participants about their preferences for the VR sickness countermeasures and experience in the VR environment. The entire study lasted approximately one and half hours.

5 RESULTS

We found that airflow is the most efficient method to reduce VR sickness based on the subjective feedback and found that cycling along a higher number of axis induces a higher VR sickness. Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [70]. For pairwise comparisons we used a Bonferroni correction. We outline all results in details in the following subsections.

5.1 VR Sickness

To assess VR sickness for different types of movement and countermeasures we analyzed Simulator Sickness Questionnaire (SSQ), Fast Motion Sickness (FMS), and Motion Sickness Susceptibility Questionnaire (MSSQ) scores.

5.1.1 SSQ for Countermeasures and Types of Movement.

5.1.1 SSQ for Countermeasures and Types of Movement. We found that three investigated *countermeasures* (airflow, FoV , and vibration) were comparably efficient for reducing VR sickness. This was shown by a non-significant effect on the overall SSQ score and the sub-score of disorientation and oculomotor ($p < 0.05$). As for the *types of movement*, we discovered that a type of movement in VR has a statistically significant main effect on the VR sickness based on the SSQ score. Cycling on a straight road had the lowest SSQ score ($M = 21.9, SD = 19.1$), followed by turns ($M = 23.5, SD = 20$) and slopes ($M = 25, SD = 19$). These differences had a statistically significant main effect on the overall SSQ score ($F(2, 46) = 4.5, p < 0.05, \eta^2 = 0.16$) and its sub-scores of disorientation ($F(2, 46) = 3.78, p < 0.05, \eta^2 = 0.14$), nausea ($F(2, 46) = 4.1, p < 0.05, \eta^2 = 0.15$) and oculomotor ($F(2, 46) = 3.44, p < 0.05, \eta^2 = 0.13$). Post-hoc pairwise comparisons showed significantly lower overall SSQ and oculomotor scores when cycling straight compared to cycling with turns ($p < 0.05$) and slopes ($p < 0.05$). The remaining pairwise comparisons were not statistically significant. Lastly, we did not observe a statistically significant interaction effects for routes*countermeasures and SSQ ($F(6, 138) = 1.1, p > 0.05, \eta^2 = 0.05$), and its sub scores of disorientation ($F(6, 138) = 1.56, p > 0.05, \eta^2 = 0.06$), nausea ($F(6, 138) = 1.1, p > 0.05, \eta^2 = 0.05$), and oculomotor ($F(6, 138) = 0.96, p > 0.05, \eta^2 = 0.04$) (Figure 7).

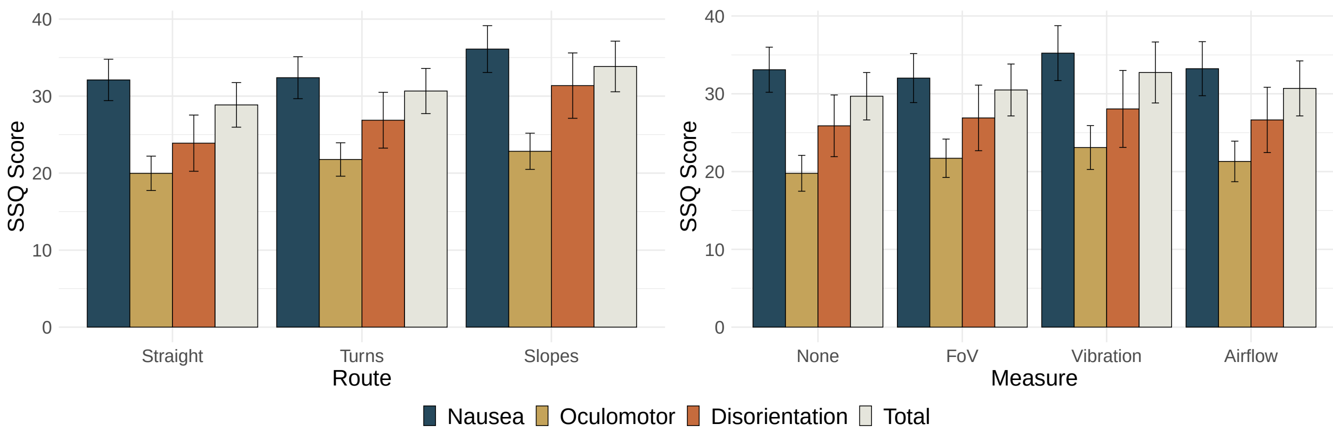

Figure 7: Overview of the total SSQ scores and its sub-scores (nausea, oculomotor, disorientation) with means and standard errors for the types of cycling routes (left) and measures to reduce VR sickness (right).

5.1.2 FMS and Motion Sickness Susceptibility. As for the development of VR sickness over time, we observed that the FMS score rises with time and this rise is seen more prominently for the routes with slopes and turns than on the straight road (Figure 8). As for the MSSQ [19], results yielded an average score of 8.77 ($SD = 7.09, min = 0.00, max = 29.00$). Based on the provided percentiles for the MSSQ-Short (n=257), the mean score corresponds to the 38.85 percentile and the maximum score to the 93.45 percentile. We found a moderate positive correlation (r=0.400, p=0.026) between the MSSQ score and average SSQ score over all conditions.

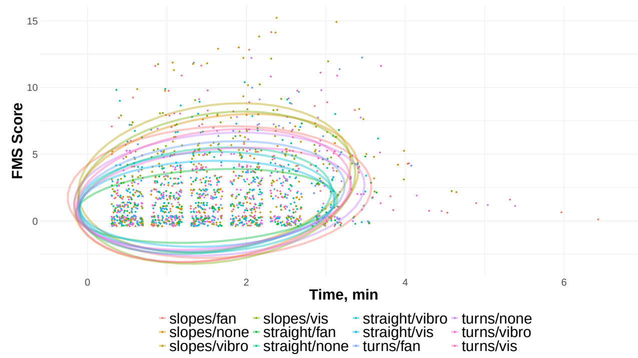

Figure 8: Overview of VR sickness tendencies over time per condition using 90% data ellipses. Data ellipses construct and return one set of x, y coordinates for each value of probability, and 90% of the ellipses would contain the underlying mean. The longer ellipses imply a constant VR sickness over a longer period of time, e.g., cycling with turns, higher ones – an increase of VR sickness, and turned ones – an increase of VR sickness over time, e.g., cycling on slopes. Given a high number of data points with the same scores, they are placed next to each other.

5.2 Cycling performance

On average, subjects were riding 21.74 km/h (SD = 5.82 km/h) on straight routes, 19.68 km/h on (SD = 4.53 km/h) routes with turns, and 18.96 km/h (SD = 6.77 km/h) on routes with turns and slopes. However, this difference was not statistically significant based on the main effects for routes ($F(2, 12) = 2.74, p > 0.05, \eta^2 = 0.31$) and countermeasures ($F(3, 18) = 0.22, p > 0.05, \eta^2 = 0.035$), and the interaction effect for routes * countermeasures ($F(6, 36) = 1.47, p > 0.05, \eta^2 = 0.2$).

As for the steering angle, we found that the standard deviation of the cycled trajectories was the lowest on *Straight* ($M = 2.41$), followed by *Slopes* ($M = 9.90$), and *Turns* ($M = 10.20$). We observed that the type of movement has a statistically significant effect on a steering angle based on the main effect for routes ($F(2, 12) = 62.03, p < 0.001, \eta^2 = 0.91$). The post-hoc analyses have shown that cycling on a straight route leads to lower changes in steering compared to cycling with turns ($p < 0.001$) and turns with slopes $p < 0.001$). Moreover, cycling with turns leads to lower changes in steering compared to turns with slopes ($p < 0.001$). As for the countermeasures, the changes in steering angle were the lowest for None ($M = 7.92$), followed by airflow ($M = 8.61$), FoV ($M = 8.84$), and Vibration ($M = 9.35$). This difference was supported by a statistically significant main effect ($F(3, 18) = 6.76, p < 0.001, \eta^2 = 0.53$). The post-hoc analyses have shown that cycling without any countermeasure leads to lower changes of steering compared to vibration ($p < 0.01$). The remaining pairs were not statistically significant.

5.3 Perceived Presence and Simulation Realism

We discovered that participants found themselves overall present in the bicycle simulation ($M = 1.42, SD = 0.83$). The sub-scales of IPQ have shown that spatial presence ($M = 1.19, SD = 1.37$) and involvement ($M = 0.13, SD = 1.42$) were above average. The experienced realism was estimated as slightly below 0 ($M = -0.60, SD = 1.54$).

As for the realism of the simulation, it was assessed high ($Md = 4, IQR = 1$). The majority of participants (N = 19) assessed airflow as the most comfortable and 23 as the most realistic measure for cycling in a VR simulator. In particular, participants mentioned that

"Wind is making me feel much better, fresh air is helpful." [P12, M, 24 years old]. The increased realism with the airflow was predominantly (N = 12) justified by the improved perception of speed. For example, P20 [M, 34 years old] noted that *"It added much to the realism. It immediately felt more like riding a real bike. Like + 100%"*.

5.4 Problems and Preferences

Regarding the subjective perception of VR sickness, twelve (out of 24) participants found that airflow leads to the lowest VR sickness regardless of the type of movement, followed by no countermeasures (N = 7), vibration (N = 3) and FoV reduction (N = 2). As for the type of movement, 20 participants mentioned that cycling straight led to the lowest VR sickness. As P12 [M, 24 years old] commented: *"As soon as something more than straight driving came in it felt a bit wrong and unexpected"*. The most common theme for this question was the lowest mismatch regarding (angular) accelerations, as stated by P15 [F, 25 years old]: *"Biggest match of movement and body position between VR and real-world"*.

Regarding the countermeasures, participants reported that vibration *"helped with motion sickness"* [P20, M, 34 year old] and *"felt comfortable"* [P21, F 23 years old]. Reduction of the Field-Of-View led to the situations when *"Curves were less noticeable"* [P6, M, 25 years old] and the changes in the Field-of-View was *"almost unnoticeable, but maybe it is better like this."* [P22, M, 24 years old]. Moreover, one participant mentioned that FoV reduction *"removed the feeling of nausea and upset stomach"* [P3, M 21 years old]. Cycling with airflow on other hand *"increased perception like a real environment and was pleasant"* [P, F, 24 years old] and it was mentioned that *"it mimics real-world airflow while cycling up or down the road, so more realistic."* [P7, F, 32 years old]. Additionally, participants reported several downsides of the proposed countermeasures. It was mentioned that vibration can be disturbing and the FoV reduction feels unnatural, as mentioned by P8 [F, 24 years old]: *"the vibration system could be a bit disturbing, the field of view reduction did not feel realistic to me"*. Moreover, vibration was perceived as *"a funny feeling"* [P22, M, 24 years old]. None of the participants mentioned negative aspects regarding the airflow countermeasure.

In general, seven participants mentioned that they had fun while riding in the VR simulator. For example, P20 [M, 34 years old] stated that *'It was the best experience of my life! Or at least I had a lot of fun and I was astonished about how realistic it all already felt! Especially when using the fan! I am a fan!"*. Two participants remarked that they would be interested in experiencing the environment with added traffic. For example, P7 [F, 32 years old] stated: *"it might be interesting to see how added traffic (and hence more stress) adds to the whole feeling of sickness"*.

6 DISCUSSION AND FUTURE WORK

In general, VR sickness in bicycle simulators can be addressed by (1) design and (2) external countermeasures. By adjustments through design, we refer to essential components of bicycle simulators, e.g., steering, turning cycling platforms, pedaling, and by external measures we name non-essential additional components, e.g., airflow, on-head vibration, reference frames. As shown by the results from our experiments, the former one has demonstrated that the VR sickness increases substantially based on the type of movement in VR simulation, and the steering with the handlebar is the method that induces the lowest VR sickness. However, the latter aspect of external countermeasures requires careful consideration, especially when cycling with turns and more importantly with turns and slopes. While the airflow has shown the highest potential to reduce VR sickness based on the subjective feedback, FoV reduction and vibration were positively perceived and can be potentially used as supplementary aids.

6.1 VR Sickness by Design

Based on the sensory mismatch theory [27], the severity of VR sickness increases for greater mismatches between what riders see through the HMD and what they feel based on their real-life motion. Hence, it does not surprise that movement along multiple axes, i.e., cycling on the trajectories with turns and slopes, significantly increases VR sickness compared to the straight trajectories. It was demonstrated for both situations: during (FMS scores) and after cycling (SSQ scores) and was further supported by the subjective feedback of the participants. This finding can be explained by a lower number of mismatches for cycling straight, which were primarily caused by accelerating and braking, compared to a higher number of mismatches caused by changes of directions, additional head movements, and reorientation in the VR world when cycling with turns and slopes. Therefore, it is crucial to consider the type of trajectories and their influence on the VR sickness of cyclists while designing experiments in VR bicycle simulators. One possible solution for that might be external controls to move the bicycle in the real world with respect to cycling trajectories via additional external forces, rotation and tilting of the bicycle platform, similar to 6-degree-of-freedom motion platform (Stewart Platform) [12, 22, 72]. These adjustments for VR bicycle simulators might bring them one step closer to the realistic movement, and therefore provide an alternative solution to reduce VR sickness by design.

As our results from the first experiment have shown, the steering using the handlebar in VR bicycle simulators leads to the lowest VR sickness. Although leaning, i.e., moving the upper body, plays an important role in bicycle steering in the real world when combined with a handlebar, it leads to a higher VR sickness without handlebar support in VR bicycle simulators. As mentioned in the discussion for the first experiment, this finding might be explained by a lower level of control over the cycling using the upper body compared to the more granular hand movements using the handlebar. Moreover, the movement of the upper body requires a higher number of head movements and additional reorientation in space, which causes a higher mismatch between the simulation and the real world, similarly to the changes in the trajectories discussed above. Therefore, it might be necessary to closely explore the combination of leaning combined with the handlebar as a steering method for VR bicycle simulators in the future to improve the designing process of VR bicycle simulators even further.

6.2 External Countermeasures to Reduce VR Sickness in Bicycle Simulators

As it was already shown in the early visions of prototypes for bicycle simulators in the book "The Wheel and cycling trade review" (dated from the year 1888) [2], airflow was an essential element of cycling experience, which was often compared to flying, given the effects of blowing wind opposing the direction of movement. Over time, airflow became not only the element of realistic cycling experience and speed [34] but was also extended to a countermeasure for reducing a mismatch between the visual and vestibular perception. However, attempts to reduce motion sickness using airflow were primarily focused on driving in car simulators [14, 21] and little do we know how this affects cycling in bicycle simulators. The results of our experiment indicate that this is true for VR bicycle simulators regardless of the type of movement. Although we did not find significant differences based on the VR sickness scores, participants' subjective preferences have clearly stated that airflow has the potential of reducing VR sickness and brings a feeling of cycling to a higher degree of realism, which is in line with the previous work regarding the car simulators [14, 21].

Surprisingly, the alternative countermeasures were not shown to be as successful as in the previous works related to walking in virtual reality using the FoV reduction [15, 33, 59, 71] and the head-mounted vibration [49], even though the former countermeasure is used in commercial applications and is part of several best practices of HMD manufacturers [10]. This can be possibly explained by a different nature of cycling movement and experience in VR compared to walking. While walking can be split into discrete elements of movement with a higher level of control and realism at the lower speed, cycling is a rather dynamic and continuous movement at the higher speed, where existing methods to reduce VR sickness might not be applicable. Therefore, a combination of head-mounted vibration and FoV reduction with the airflow might require a more careful design based on the type of movement in VR, e.g., the simulation provides constant airflow but employs vibrations only when turning. Alternatively, future work might need to consider alternative countermeasures, such as reference frame [68, 69] or galvanic feedback [20, 35, 67].

6.3 Employing Off-the-Shelf Bicycle Simulators

Some existing solutions for VR bicycle simulators, e.g., Xtrematic [11], already provide a wind-blowing effect compared to the older versions of bicycle simulators that employ fixed displays in front of a cyclist [12]. Typically, designers of VR bicycle simulators equip with a targeted wind flow generation system adding more realism and thrill to sensations. However, the airflow can not only be used to amplify the effects of cycling sensation but also has the potential to reduce VR sickness, which in turn will prolong the duration of cycling and create a more joyful experience. Thus, adding airflow to VR bicycle simulators coupled with the cycling speed and the type of landscape may be a viable option. As a result, off-the-shelf solutions can be leveraged without modifying too many custom hardware and software systems.

[10] https://developer.oculus.com/resources/locomotion-design-reduce-optic-flow/,https://rebellion.com/games/sniper-elite-vr/

[11] https://xtrematic.com/x-bike/

[12] https://www.zwift.com, https://www.bkool.com/en/cycling-simulator

7 LIMITATIONS

The VR simulation environment used in both of our evaluations was purely visual and did not include environmental sounds, traffic, or background noise. However, excluding these aspects from the simulation allowed us to explore the effects of steering and types of movement without external influences. Creating an enjoyable and realistic VR cycling experience for health rehabilitation and entertainment still has a long way to go and may require further enhancements to the virtual environment to increase realism. With our work, we aimed to get one step closer to VR cycling experience with lower VR sickness, but given the sample size, limited age range between 21 and 34 years, and cultural background of the participants, it might be difficult to generalize our results to a larger group of cyclists, which needs to be considered in future work. However, with these results, we provide the first empirical evaluation of steering methods and countermeasures against VR sickness in stationary bicycle simulators. In addition, we conducted the second experiment during the summer, which may have influenced the effect of airflow on participants' perception. Nevertheless, it was still perceived as the most realistic and enjoyable way to enhance the VR cycling experience. In the first study, we used a coin collection task to guide participants through the cycling simulation, which may have distracted them from the actual study objective. We acknowledge that VR sickness increases with age and time spent in the VR simulation, and our experiments focused primarily on younger participants (between 21 and 34 years of age), and the duration of both experiments was less than two hours. Therefore, future studies need to be conducted with other age groups and different duration of cycling.

8 CONCLUSION

In this paper, we investigated methods to reduce VR sickness in bicycle simulators. For this, we conducted two controlled lab experiments focused on two main causes of VR sickness: (1) steering and (2) movement through space. We found that the handlebar steering method leads to the lowest VR sickness and has the highest usability. Moreover, we have shown that the VR sickness depends on the type of movement in VR simulation and increases when the VR landscape provides turns and slopes. Lastly, airflow suggests to be the most promising method to reduce VR sickness for all three types of trajectories, but FoV reduction and vibration can be potentially used as supplementary aids.

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REFERENCES

[1] Majed Al Zayer, Isayas B. Adhanom, Paul MacNeilage, and Eelke Folmer. 2019. *The Effect of Field-of-View Restriction on Sex Bias in VR Sickness and Spatial Navigation Performance.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300584

[2] Anonymous. 1888. *The Wheel and cycling trade review.* Wheel and Cycling Trade Review. https://library.si.edu/digital-library/book/wheelcy18211896121897newy

[3] Shani Batcir, Omri Lubovsky, Yaacov G. Bachner, and Itshak Melzer. 2021. The Effects of Bicycle Simulator Training on Anticipatory and Compensatory Postural Control in Older Adults: Study Protocol for a Single-Blind Randomized Controlled Trial. *Frontiers in Neurology* 11 (2021), 1869. https://doi.org/10.3389/fneur.2020.614664

[4] Pauline Bimberg, Tim Weissker, and Alexander Kulik. 2020. 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)*. 464–467. https://doi.org/10.1109/VRW50115.2020.00098

[5] E. Blana. 1996. *Driving Simulator Validation Studies: A Literature Review.* Technical Report Working Paper 480. Leeds, UK. https://eprints.whiterose.ac.uk/2111/

[6] Martyna Bogacz, Stephane Hess, Chiara Calastri, Charisma F. Choudhury, Alexander Erath, Michael A. B. van Eggermond, Faisal Mushtaq, Mohsen Nazemi, and Muhammad Awais. 2020. Comparison of Cycling Behavior between Keyboard-Controlled and Instrumented Bicycle Experiments in Virtual Reality. *Transportation Research Record* 2674, 7 (2020), 244–257. https://doi.org/10.1177/0361198120921850

[7] Jelte E. Bos, Sjoerd C. de Vries, Martijn L. van Emmerik, and Eric L. Groen. 2010. The effect of internal and external fields of view on visually induced motion sickness. *Applied Ergonomics* 41, 4 (July 2010), 516–521. https://doi.org/10.1016/j.apergo.2009.11.007

[8] Zekun Cao, Jason Jerald, and Regis Kopper. 2018. Visually-Induced Motion Sickness Reduction via Static and Dynamic Rest Frames. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Reutlingen, 105–112. https://doi.org/10.1109/VR.2018.8446210

[9] Gianpaolo U. Carraro, Mauricio Cortes, John T. Edmark, and J. Robert Ensor. 1998. The peloton bicycling simulator. In *Proceedings of the third symposium on Virtual reality modeling language - VRML '98*. ACM Press, Monterey, California, United States, 63–70. https://doi.org/10.1145/271897.274372

[10] Eunhee Chang, Hyun Taek Kim, and Byounghyun Yoo. 2020. Virtual Reality Sickness: A Review of Causes and Measurements. *International Journal of Human–Computer Interaction* 36, 17 (2020), 1658–1682. https://doi.org/10.1080/10447318.2020.1778351

[11] L. Dominjon, Anatole Lécuyer, Jean-Marie Burkhardt, Paul Richard, and S. Richir. 2005. Influence of Control/Display Ratio on the Perception of Mass of Manipulated Objects in Virtual Environments. In *IEEE International Conference on Virtual Reality*. Bonn, Germany, 19–25. https://doi.org/10.1109/VR.2005.1492749

[12] Dong-Soo Kwon, Gi-Hun Yang, Chong-Won Lee, Jae-Cheol Shin, Youngjin Park, Byungbo Jung, Doo Yong Lee, Kyungno Lee, Soon-Hung Han, Byoung-Hyun Yoo, Kwang-Yun Wohn, and Jung-Hyun Ahn. 2001. KAIST interactive bicycle simulator. In *Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation*, Vol. 3. IEEE, Seoul, South Korea, 2313–2318. https://doi.org/10.1109/ROBOT.2001.932967

[13] Natalia Dużmańska, Paweł Strojny, and Agnieszka Strojny. 2018. Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness. *Frontiers in Psychology* 9 (2018), 2132. https://doi.org/10.3389/fpsyg.2018.02132

[14] Sarah D'Amour, Jelte E. Bos, and Behrang Keshavarz. 2017. The efficacy of airflow and seat vibration on reducing visually induced motion sickness. *Experimental Brain Research* 235, 9 (Sept. 2017), 2811–2820. https://doi.org/10.1007/s00221-017-5009-1

[15] Ajoy S Fernandes and Steven K. Feiner. 2016. Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. 201–210. https://doi.org/10.1109/3DUI.2016.7460053

[16] Sebastian Freitag, Dominik Rausch, and Torsten Kuhlen. 2014. Reorientation in virtual environments using interactive portals. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 119–122. https://doi.org/10.1109/3DUI.2014.6798852

[17] P. Gamito, Jorge Oliveira, D. Morais, André Baptista, N. Santos, F. Soares, T. Saraiva, and P. Rosa. 2010. Training presence: the importance of virtual reality experience on the "sense of being there". *Studies in health technology and informatics* 154 (2010), 128–33.

[18] Stuart T Godley, Thomas J Triggs, and Brian N Fildes. 2002. Driving simulator validation for speed research. *Accident Analysis & Prevention* 34, 5 (2002), 589–600. https://doi.org/10.1016/S0001-4575(01)00056-2

[19] John F Golding. 1998. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain Research Bulletin* 47, 5 (1998), 507–516. https://doi.org/10.1016/S0361-9230(98)00091-4

[20] Germán Gálvez-García, Marion Hay, and Catherine Gabaude. 2015. Alleviating Simulator Sickness with Galvanic Cutaneous Stimulation. *Human Factors* 57, 4 (2015), 649–657. https://doi.org/10.1177/0018720814554948

[21] Jake Harrington, Benjamin Williams, and Christopher Headleand. 2019. A Somatic Approach to Combating Cybersickness Utilising Airflow Feedback. *Computer Graphics and Visual Computing (CGVC)* (2019), 9 pages. https://doi.org/10.2312/CGVC.20191256

[22] R. Herpers, W. Heiden, M. Kutz, D. Scherfgen, U. Hartmann, J. Bongartz, and O. Schulzyk. 2008. FIVIS Bicycle Simulator: An Immersive Game Platform for Physical Activities. In *Proceedings of the 2008 Conference on Future Play: Research, Play, Share* (Toronto, Ontario, Canada) *(Future Play '08)*. Association for Computing Machinery, New York, NY, USA, 244–247. https://doi.org/10.1145/1496984.1497035

[23] Nico A. Kaptein, Jan Theeuwes, and Richard van der Horst. 1996. Driving Simulator Validity: Some Considerations. *Transportation Research Record* 1550, 1 (1996), 30–36. https://doi.org/10.1177/0361198196155000105

[24] S. Katsigiannis, R. Willis, and N. Ramzan. 2019. A QoE and Simulator Sickness Evaluation of a Smart-Exercise-Bike Virtual Reality System via User Feedback and Physiological Signals. *IEEE Transactions on Consumer Electronics* 65, 1 (Feb. 2019), 119–127. https://doi.org/10.1109/TCE.2018.2879065

[25] Oliver Beren Kaul and Michael Rohs. 2017. *HapticHead: A Spherical Vibrotactile Grid around the Head for 3D Guidance in Virtual and Augmented Reality*. Association for Computing Machinery, New York, NY, USA, 3729–3740. https://doi.org/10.1145/3025453.3025684

[26] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[27] Randall L Kohl. 1983. Sensory conflict theory of space motion sickness: an anatomical location for the neuroconflict. *Aviation, space, and environmental medicine* (1983).

[28] Panagiotis Kourtesis, Simona Collina, Leonidas A. A. Doumas, and Sarah E. MacPherson. 2019. Validation of the Virtual Reality Neuroscience Questionnaire: Maximum Duration of Immersive Virtual Reality Sessions Without the Presence of Pertinent Adverse Symptomatology. *Frontiers in Human Neuroscience* 13 (2019). https://doi.org/10.3389/fnhum.2019.00417

[29] Ernst Kruijff, Alexander Marquardt, Christina Trepkowski, Robert W. Lindeman, Andre Hinkenjann, Jens Maiero, and Bernhard E. Riecke. 2016. On Your Feet! Enhancing Vection in Leaning-Based Interfaces through Multisensory Stimuli. In *Proceedings of the 2016 Symposium on Spatial User Interaction* (Tokyo, Japan) *(SUI '16)*. Association for Computing Machinery, New York, NY, USA, 149–158. https://doi.org/10.1145/2983310.2985759

[30] Joseph J. LaViola. 2000. A Discussion of Cybersickness in Virtual Environments. *SIGCHI Bull.* 32, 1 (Jan. 2000), 47–56. https://doi.org/10.1145/333329.333344

[31] B. Lenggenhager, C. Lopez, and O. Blanke. 2008. Influence of galvanic vestibular stimulation on egocentric and object-based mental transformations. *Exp. Brain Res.* 184 (2008), 211–221.

[32] Mertens Lieze, Van Cauwenberg Jelle, Deforche Benedicte, Van de Weghe Nico, Matthys Mario, and Delfien Van Dyck. 2020. Using virtual reality to investigate physical environmental factors related to cycling in older adults: A comparison between two methodologies. *Journal of Transport & Health* 19 (Dec. 2020), 100921. https://doi.org/10.1016/j.jth.2020.100921

[33] Kyungmin Lim, Jaesung Lee, Kwanghyun Won, Nupur Kala, and Tammy Lee. 2020. A novel method for VR sickness reduction based on dynamic field of view processing. *Virtual Reality* (July 2020). https://doi.org/10.1007/s10055-020-00457-3

[34] Markus Löchtefeld, Antonio Krüger, and Hans Gellersen. 2016. DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (Gothenburg, Sweden) *(NordiCHI '16)*. Association for Computing Machinery, New York, NY, USA, Article 40, 10 pages. https://doi.org/10.1145/2971485.2971513

[35] T. Maeda, H. Ando, and M. Sugimoto. 2005. Virtual acceleration with galvanic vestibular stimulation in a virtual reality environment. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* 289–290. https://doi.org/10.1109/VR.2005.1492799

[36] Andrii Matviienko, Swamy Ananthanarayan, Shadan Sadeghian Borojeni, Yannick Feld, Wilko Heuten, and Susanne Boll. 2018. Augmenting Bicycles and Helmets with Multimodal Warnings for Children. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Barcelona, Spain) *(MobileHCI '18)*. Association for Computing Machinery, New York, NY, USA, Article 15, 13 pages. https://doi.org/10.1145/3229434.3229479

[37] Andrii Matviienko, Swamy Ananthanarayan, Stephen Brewster, Wilko Heuten, and Susanne Boll. 2019. Comparing Unimodal Lane Keeping Cues for Child Cyclists. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia* (Pisa, Italy) *(MUM '19)*. Association for Computing Machinery, New York, NY, USA, Article 14, 11 pages. https://doi.org/10.1145/3365610.3365632

[38] Andrii Matviienko, Swamy Ananthanarayan, Abdallah El Ali, Wilko Heuten, and Susanne Boll. 2019. NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300850

[39] Jaap P Meijaard, Jim M Papadopoulos, Andy Ruina, and Arend L Schwab. 2007. Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review. *Proceedings of the Royal society A: mathematical, physical and engineering sciences* 463, 2084 (2007), 1955–1982. https://doi.org/10.1098/rspa.2007.1857

[40] Lynn Meuleners and Michelle Fraser. 2015. A validation study of driving errors using a driving simulator. *Transportation Research Part F: Traffic Psychology and Behaviour* 29 (2015), 14–21. https://doi.org/10.1016/j.trf.2014.11.009

[41] Justin Mittelstaedt, Jan Wacker, and Dirk Stelling. 2018. Effects of display type and motion control on cybersickness in a virtual bike simulator. *Displays* 51 (2018), 43–50. https://doi.org/10.1016/j.displa.2018.01.002

[42] William F Moroney and Michael G Lilienthal. 2008. Human factors in simulation and training. *Human Factors in Simulation and Training. CRC Press* (2008), 3–38.

[43] Kimberly Myles and Joel T Kalb. 2010. *Guidelines for head tactile communication.* Technical Report. Army Research Lab Aberdeen Proving Ground Md Human Research And Engineering.

[44] Kimberly Myles and Joel T. Kalb. 2013. Head Tactile Communication: Promising Technology With the Design of a Head-Mounted Tactile Display. *Ergonomics in Design* 21, 2 (2013), 4–8. https://doi.org/10.1177/1064804613477861

[45] Kimberly Myles and Joel T Kalb. 2015. *An Evaluation of Signal Annoyance for a Head-Mounted Tactile Display.* Technical Report. ARMY RESEARCH LAB ABERDEEN PROVING GROUND MD HUMAN RESEARCH AND ENGINEERING.

[46] Diederick C. Niehorster, Li Li, and Markus Lappe. 2017. The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research. *i-Perception* 8, 3 (June 2017), 2041669517708205. https://doi.org/10.1177/2041669517708205

[47] Steve O'Hern, Jennie Oxley, and Mark Stevenson. 2017. Validation of a bicycle simulator for road safety research. *Accident Analysis & Prevention* 100 (2017), 53–58. https://doi.org/10.1016/j.aap.2017.01.002

[48] Andrew Paroz and Leigh Ellen Potter. 2018. Impact of air flow and a hybrid locomotion system on cybersickness. In *Proceedings of the 30th Australian Conference on Computer-Human Interaction.* ACM, Melbourne Australia, 582–586. https://doi.org/10.1145/3292147.3292229

[49] Yi-Hao Peng, Carolyn Yu, Shi-Hong Liu, Chung-Wei Wang, Paul Taele, Neng-Hao Yu, and Mike Y. Chen. 2020. *WalkingVibe: Reducing Virtual Reality Sickness and Improving Realism While Walking in VR Using Unobtrusive Head-Mounted Vibrotactile Feedback.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376847

[50] Lisa Rebenitsch and Charles Owen. 2016. Review on cybersickness in applications and visual displays. *Virtual Reality* 20, 2 (2016), 101–125. https://doi.org/10.1007/s10055-016-0285-9

[51] Roy A. Ruddle, Ekaterina Volkova, and Heinrich H. Bülthoff. 2011. Walking Improves Your Cognitive Map in Environments That Are Large-Scale and Large in Extent. *ACM Trans. Comput.-Hum. Interact.* 18, 2, Article 10 (July 2011), 20 pages. https://doi.org/10.1145/1970378.1970384

[52] Christina (Missy) Rudin-Brown, Amy Williamson, and Michael Lenne. 2009. *Can driving simulation be used to predict changes in real-world crash risk? [Monash University Accident Research Centre - Report 299].* Monash University Accident Research Centre, Australia. https://eprints.qut.edu.au/80745/

[53] Yoshiaki Saito, Kazumasa Kawashima, and Masahito Hirakawa. 2020. Effectiveness of a Head Movement Interface for Steering a Vehicle in a Virtual Reality Driving Simulation. *Symmetry* 12, 10 (Oct. 2020), 1645. https://doi.org/10.3390/sym12101645

[54] Filip Schramka, Stefan Arisona, Michael Joos, and Alexander Erath. 2017. Development of Virtual Reality Cycling Simulator. (2017). https://doi.org/10.3929/ethz-b-000129869

[55] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments* 10, 3 (06 2001), 266–281. https://doi.org/10.1162/105474601300343603

[56] A. Seay, David Krum, Larry Hodges, and William Ribarsky. 2002. Simulator sickness and presence in a high field-of-view virtual environment. 784–785. https://doi.org/10.1145/506443.506596

[57] Kay M. Stanney, Robert S. Kennedy, and Julie M. Drexler. 1997. Cybersickness is Not Simulator Sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 41, 2 (1997), 1138–1142. https://doi.org/10.1177/107118139704100292

[58] Sung Hwan Jeong, Yong Jun Piao, Woo Suk Chong, Yong Yook Kim, Sang Min Lee, Tae Kyu Kwon, Chul Un Hong, and Nam Gyun Kim. 2005. The Development of a New Training System for Improving Equilibrium Sense Using a Virtual Bicycle Simulator. In *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference.* 2567–2570. https://doi.org/10.1109/IEMBS.2005.1616993

[59] Joel Teixeira and Stephen Palmisano. 2020. Effects of dynamic field-of-view restriction on cybersickness and presence in HMD-based virtual reality. *Virtual Reality* (Aug. 2020). https://doi.org/10.1007/s10055-020-00466-2

[60] Léo Terziman, Maud Marchal, Franck Multon, Bruno Arnaldi, and Anatole Lecuyer. 2012. The King-Kong Effects: Improving sensation of walking in VR with visual and tactile vibrations at each step. In *2012 IEEE Symposium on 3D User Interfaces (3DUI).* 19–26. https://doi.org/10.1109/3DUI.2012.6184179

[61] Jan Törnros. 1998. Driving behaviour in a real and a simulated road tunnel—a validation study. *Accident Analysis & Prevention* 30, 4 (1998), 497–503. https://doi.org/10.1016/S0001-4575(97)00099-7

[62] Daniela Ullmann, Julian Kreimeier, Timo Götzelmann, and Harald Kipke. 2020. BikeVR: A Virtual Reality Bicycle Simulator towards Sustainable Urban Space and Traffic Planning. In *Proceedings of the Conference on Mensch Und Computer* (Magdeburg, Germany) *(MuC '20).* Association for Computing Machinery, New York, NY, USA, 511–514. https://doi.org/10.1145/3404983.3410417

[63] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks. 1999. Walking > Walking-in-Place > Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99).* ACM Press/Addison-Wesley Publishing Co., USA, 359–364. https://doi.org/10.1145/311535.311589

[64] Tamara von Sawitzky, Philipp Wintersberger, Andreas Löcken, Anna-Katharina Frison, and Andreas Riener. 2020. Augmentation Concepts with HUDs for Cyclists to Improve Road Safety in Shared Spaces. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20).* Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3383022

[65] Jia Wang and Robert W. Lindeman. 2012. Comparing isometric and elastic surfboard interfaces for leaning-based travel in 3D virtual environments. In *2012 IEEE Symposium on 3D User Interfaces (3DUI).* 31–38. https://doi.org/10.1109/3DUI.2012.6184181

[66] Séamas Weech, Jae Moon, and Nikolaus F. Troje. 2018. Influence of bone-conducted vibration on simulator sickness in virtual reality. *PLOS ONE* 13, 3 (03 2018), 1–21. https://doi.org/10.1371/journal.pone.0194137

[67] Séamas Weech and Nikolaus F. Troje. 2017. Vection Latency Is Reduced by Bone-Conducted Vibration and Noisy Galvanic Vestibular Stimulation. *Multisensory Research* 30, 1 (2017), 65 – 90. https://doi.org/10.1163/22134808-00002545

[68] David Matthew Whittinghill, Bradley Ziegler, T. Case, and B. Moore. 2015. Nasum virtualis: A simple technique for reducing simulator sickness. In *Games Developers Conference (GDC).* 74.

[69] C. Wienrich, C. K. Weidner, C. Schatto, D. Obremski, and J. H. Israel. 2018. A Virtual Nose as a Rest-Frame - The Impact on Simulator Sickness and Game Experience. In *2018 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games).* 1–8. https://doi.org/10.1109/VS-Games.2018.8493408

[70] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. *The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures.* Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963

[71] Fei Wu and Evan Suma Rosenberg. 2019. Combining Dynamic Field of View Modification with Physical Obstacle Avoidance. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* IEEE, Osaka, Japan, 1882–1883. https://doi.org/10.1109/VR.2019.8798015

[72] Hwa Jen Yap. 2018. Design and development of a spatial immersive track cycling simulator. *Malaysian Journal of Movement, Health & Exercise* 7, 2 (July 2018). https://doi.org/10.15282/mohe.v7i2.217

[73] Hwa Jen Yap, Tan Cee Hau, Zahari Taha, Chang Siow Wee, Sivadas Chanda Sekaran, and Wan Wei Lim. 2018. Design and development of a spatial immersive track cycling simulator. *Malaysian Journal of Movement, Health & Exercise* 7, 2 (2018). https://doi.org/10.15282/mohe.v7i2.217