Development and Evaluation of a Motion-based VR Bicycle Simulator

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Fig. 1. Participants completed a test track multiple times with either a strong tilt (1), a weaker tilt with less aggressive onset (2), and a baseline condition without any tilt (3).

Bicycle simulators are becoming an increasingly used research tool. However, due to the complex cycling dynamics, these simulators have issues of simulator sickness and perceived realism. A potential method to address these issues could be providing a motion-based tilting function. Some bicycle simulators with tilt functionality have already been presented but still lack a systematic evaluation. In this work, we present a motion-based bicycle simulator without centrifugal force simulation and the results from a user study that compared different tilt modes. N=31 participants completed a study in virtual reality with a strong and a weak tilt mode, as well as a baseline condition without movement. We discovered that weak tilting could significantly improve the cycling realism without decreasing cycling performance and simulator sickness. Furthermore, our research suggests that there is a sweet spot for a tilting function, which facilitates a balance between presence/immersion and simulator sickness.

CCS Concepts: • **Human-centered computing** → **Laboratory experiments**; **Virtual reality**.

Additional Key Words and Phrases: Bicycle simulators, cycling, traffic safety, virtual reality, simulator sickness, empirical evaluation, user study

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1 INTRODUCTION

Bicycles are becoming an increasingly popular alternative to automobiles, which should be considered a positive development since bikes require less space, have a lower weight-to-power ratio, and are a much more sustainable mode of transportation. Still, cyclists are increasingly involved in accidents, and their chances of suffering severe injuries increase due to the introduction of pedelecs and electric bicycles, which allow higher speeds [53]. While traditional vehicles have experienced a massive safety gain in the last decades, the potential of active safety and technical assistance for bicycles is up to date, largely unexploited. Consequently, cycling safety has become an increasingly relevant research topic [26, 36, 38, 39]. Recent CHI [48] and Mobile HCI [37] workshops have addressed the topic, and multiple works have proposed "smart" systems to foster cycling safety and convenience [1, 32–35, 61].

In this context, bicycle simulators are important research tools that facilitate indoor evaluations in safe laboratory conditions. While simple simulations (i.e., ergometers or bike trainers with training apps) have already found their way into living rooms to support entertainment, training, and rehabilitation [18, 21], more complex simulators are typically developed by the researchers themselves. Many existing solutions, for example, the simulators used in [34, 43, 59, 61], are static, i.e., they miss physical movement in space and do not accurately reproduce the motion dynamics necessary to convey a realistic cycling experience. This can lead to increased simulator sickness [42] and decreased immersion since the visual feedback present in VR headsets does not match the expected bodily sensations. Such "vestibular conflicts" can negatively influence cycling performance [27] and increase participant dropout rates [7, 12, 62]. To address this, researchers have employed adjusted experimental designs, such as the restriction to straight trajectories without curves [61]. Matviienko et al. [40] have systematically compared different control input methods and driving scenarios and showed that turns and slopes increase simulator sickness compared to straight trajectories. Additionally, the authors demonstrated that external countermeasures such as an airflow simulation can be beneficial but also suggest addressing physical motion in simulator design in the future [40]. Currently, we still lack an understanding of how simulator movement (i.e., roll, pitch, or rotation) could support avoiding the mismatch between visual and body perception. We hypothesize that physical motion (particularly simulator tilting) can improve perceived realism and reduce simulator sickness and built a motion-based bicycle simulator to investigate these claims.

Developing sophisticated motion-based simulators is not an easy task, as it requires resolving the complex relationship between hardware, virtual environments, and human factors [6]. Modern vehicle or flight simulators try to reproduce the physical forces drivers/passengers experience accurately. Frequently, this requires compromise – for example, vehicle simulators mounted on a hexapod platform with 6 degrees of freedom utilize an outward roll to simulator forces in curves. In contrast, the most sophisticated driving simulators can additionally rotate (like the KITE DriverLab[1]) or even move (like the Mercedes AMG Driving Simulator[2]) the platform to create more accurate sensations. In contrast, motorcycle simulators, which can be considered as the "nearest relative" to bicycle simulators, typically simulate tilt [3] rather than forces. However, tilting

[1]https://kite-uhn.com/lab/driverlab
[2]https://www.mercedes-amg.com/en/world-of-amg/stories/inside-amg/AMG-Driving-Simulator.html

is not necessarily physically accurate. Regarding the dynamics of two-wheelers when driving curves, centrifugal forces superimpose the gravitational force – otherwise, a rider would feel "hanging to the side". Consequently, some motorcycle simulators scale down the roll angle to provide a more realistic perception [66]. Another work on the roll angle of motorcycle simulators conducted by Shahar et al. [51] concludes that a certain roll angle is necessary as experienced motorcyclists consider "proximity to the ground when leaning [e.g., into a curve] an important component in the motorcycle experience". Still, there are other differences between motorcycles and bicycles. Motorcycles have thicker tires, much more power, and different weight distribution between the vehicle and the rider. According to Kooijman and Schwab [25], cyclists do not only control the vehicle, they "contribute significantly to the mechanical system", and in contrast to motorcycles, a rider's weight accounts for up to 90% of the complete system's mass. Because of such differences, knowledge from motorcycle simulators cannot be transferred to bicycle simulators.

Consequently, this paper aims to systematically evaluate the effect of bicycle simulator tilt on perceived realism, user experience, simulator sickness, and driving behavior. For this, we designed a motion-based bicycle simulator that facilitates rolling around the longitudinal axis and developed two tilting modes for evaluation – one derived from physically accurate tilting as present in reality (regarding the relationship of speed, curve radius, and tilting) and an improved "weak" tilt mode with less extreme onset behavior. Furthermore, both modes were linearly mapped to 10 (from -5 to +5) degrees as provided by the utilized motion platform. We aimed to provide a more realistic perception of VR cycling than static simulators without motion. With this paper, we contribute to the challenge of building more accurate and realistic VR bicycle simulators in the future.

2 PERCEIVED REALISM AND SIMULATOR SICKNESS IN BICYCLE SIMULATOR RESEARCH

According to Slater [55], immersion is a property of a VR system that describes the "extent to which a VR system can support natural sensorimotor contingencies for perception", while presence is the human response of feeling to be in that environment [54]. Simulator sickness (also sometimes referred to as VR sickness, cybersickness, or visually-induced motion sickness) results from a conflict between expected and observed sensory signals [63]. Weech et al. [63] suggest that presence and (cyber)sickness have shared causes and show a negative relationship. Current bicycle simulators exist at different levels of fidelity. To reduce sensory conflicts in bicycle simulators, researchers have utilized (1) visuo-vestibular and (2) hardware modifications. We outline these two approaches and existing tilt function modifications in detail in the following.

2.1 Visuo-Vestibular and Visual Modifications

Researchers have previously employed visuo-vestibular and visual modifications to explore the ways of reducing VR sickness [10, 29, 46, 56]. The visuo-vestibular modification utilizes physical stimulation around the vestibular system. It typically includes galvanic feedback [14, 31, 65], airflow [7, 16], bone-conductive vibration [64, 65], vibration on a seat [7], head [45], and feet [28, 58] to enhance participants' sensation of self-motion. The visual modification, on the other hand, facilitates visual changes in the perception of VR environments from the user's point of view. Some of the examples within visual modifications include blurring, vignette, blink [13, 47, 60]. Moreover, motion sickness also depends on the type of visual information presentation, i.e., large display, CAVE environment, or VR, and the availability of auditory cues, or airflow simulation [19, 42, 59]. Low-fidelity simulators can be built with off-the-shelf ergometers. Using such a device, Mittelstaedt et al. [42] demonstrated that participants experienced a lower level of motion sickness with a large display compared to VR glasses.

2.2 Hardware Modifications

An alternative way to align sensory perceptions is via design modifications in the physical setup of bicycle simulators. One possible option would be to place an actual bicycle on a bike trainer, which exists both in the form of wheel-on, i.e., rear-wheel spinning a reel [61]), or direct trainers, i.e., rear-wheel removed and gearbox directly attached to the device with the advantage of less latency and friction of the tire [57]. For lateral driving, some projects use potentiometers, rotary encoders, optical tracking, or VR controllers to measure the rotation of the handlebar [2, 57, 59]. An alternative option would be to estimate the positioning of the riders' body weight, i.e., dynamic center of mass, by using load cells [8]. However, a study by Matviienko et al. [40] suggests that handlebar input induces less simulator sickness than body positioning (i.e., leaning), at least for static simulators. As for the high-fidelity motion-based simulators, the FIVIS simulator [19] uses a hydraulic platform, which supports six degrees of freedom. Another simulator was presented by Yamaguchi et al. [67], who implemented a tilt function by connecting the rear wheel to an industrial servomotor. However, both projects contribute technical aspects of the bicycle simulators without an empirical evaluation of participants' experience.

2.3 Tilt Function

A tilt function as a mechanism to physically move bicycle simulators is not only possible in an active, i.e., motors controlling the tilt angle, but also in a passive way. Passive tilting is achieved by responding to the rider's weight shifts. Such functionality can be achieved by passively following the actions and movements of a cyclist using a motion platform [15] or by using a suspension system [52]. The work by Shoman and Imine [52] contains an evaluation of simulator sickness, but it does not provide information about how the tilt feature influences motion sickness and perceived realism. Still, simulator tilt is not merely a binary "on or off" feature but can (and must) be implemented in various nuances. For example, physical calculations show that driving a curve with a 10-meter radius at 25 kilometers per hour would result in a tilt angle of 26.18 degrees. Since cycling in a simulator does not include centrifugal forces, such a large tilt angle would result in unrealistic gravitational force. The tilt could be either cut at a certain level or dumped to prevent such a situation. Therefore, to provide a potentially realistic perception in virtual reality, it is known that humans can be tricked with alternative or scaled forces [66].

2.4 Bicycle Simulator Designs in Existing Literature

To derive best practices for the design of our bicycle simulator, we reviewed existing works and categorized the simulator designs concerning used sensors, actuators, simulator types, visualization methods, and their primary research purpose (see Table 1). Therefore, we searched on Google Scholar for relevant publications and scanned the referenced literature in well-known works (we do not claim this evaluation to be comprehensively following a systematic review process). Our results (based on 18 simulators) show that the majority use bicycles on a stationary smart or roller trainer. We found 11 designs that utilize head-mounted displays (HMDs) with virtual reality. We distinguish between speed and braking sensors for our review due to the differing characteristics of rear-wheel spinning and direct trainers. With the former, a braking action decreases the spinning speed of the rear wheel, which directly influences the speed sensed by the trainer. In contrast, a system with a direct trainer no longer has a rear wheel attached, so any braking actuation needs to be captured with extra sensors (the same issue is present when using an ergometer). Also, airstream simulation is becoming an increasingly popular (and affordable) external addition to improve the cycling experience. We found three concepts that utilize passive tilting and another three that describe the use of a motion platform. Although some works have investigated simulator sickness

Ref.	Sensors	Actuators	Simulator Type	Visualization	Research Purpose
[42]	Speed, Steering, Braking	-	Stationary bicycle	HMD, Screen	Simulator Sickness Investigation
[18]	Speed, Steering, Braking, Fork, Inclanation	Motion platform	(Active) Motion-based bicycle	Multi-screen	Bicycle simulator development
[30]	Speed, Steering	Airstream	Stationary ergometer	HMD	Effective training
[17]	Speed, Steering, Braking	Handlebar, Braking	Stationary bicycle	HMD	Bicycle simulator development
[61]	Speed, Steering	-	Stationary bicycle	HMD	Traffic safety
[67]	Speed, Steering, Braking	Tilting	(Active) Motion-based bicycle	Multi-screen	Traffic safety
[32]	Speed, Steering, Braking	Visual, tactile, auditory feedback	Stationary bicycle	Projection	Traffic safety
[2]	Speed, Motion Capture system	Motion platform	(Active) Motion-based ergometer	Screen	Training and health
[5]	Speed, Steering	Resistance	Stationary bicycle	HMD	Bicycle simulator development
[59]	Speed, Steering	-	Stationary bicycle	HMD	Urban traffic planning
[57]	Speed, Steering, Braking	-	Stationary bicycle	Screen	Bicycle simulator development
[22]	Speed, Steering	-	Stationary bicycle	Multi-screen	Traffic planning and user modeling
[44]	Speed, Steering, Braking	-	Stationary bicycle	HMD	Traffic safety
[43]	Speed, Steering, Braking	Resistence	Stationary bicycle	HMD	Traffic safety
[41]	Speed, Steering, Braking	Airstream	Stationary bicycle	HMD	Simulator Sickness Investigation
[8]	Speed, Steering, Braking, Body Weight	Airstream, Haptic response	(Passive) Motion-based bicycle	HMD	Bicycle simulator development User experience investigation
[52]	Speed, Steering, Braking	Airstream, Haptic response, Steering response, flywheel	(Passive) Motion-based bicycle	Multi-screen	Bicycle simulator development
[15]	Speed, Steering via button	Airstream	(Passive) Motion-based bicycle	HMD	Bicycle simulator development Traffic safety

Table 1. Existing bicycle simulators found in literature with their sensors and actuators, type of simulator, visualization method, and main research purpose in the corresponding publication.

or psychological concepts such as user experience, to our best knowledge, a systematic assessment of perceived realism and simulator sickness in the context of simulator tilting is still missing.

3 TECHNICAL SETUP

To build the bicycle simulator (an overview of the different components used is depicted in Figure 2), we used an ordinary city bike (28-inch wheels) and mounted it on a Garmin Tacx Flux 2[3] smart, direct bicycle trainer. We favored a direct trainer with a cassette to not suffer the slight loss of friction that would be present on a roller trainer, and the chosen device also supports inducing resistance. The current speed of the bike is gathered via Bluetooth and the supported

[3]https://www.garmin.com/en-US/p/690887

Fitness Machine Service Protocol (FTMS) that supports both reading (speed) and writing (resistance) data. The steering angle is measured using a potentiometer attached to the fork with 3D-printed components consisting of pulley wheels and a belt. The value of the potentiometer is mapped to a range from -90° to 90°, representing the maximum left and right handlebar rotation. Also, we placed a servomotor on top of the handlebar to control the steering angle via software. In future work, we will investigate how this motor can be used to simulate uneven surfaces. However, for the experiment as presented, we only utilized the motor's internal resistance to prevent an unnatural rotation in case the platform is tilted and to support a more stable feeling from the perspective of study participants. Braking functionality is achieved with thin-film pressure sensors (range 0-20kg, 300g sensitivity) placed between the front and the wheels' rim and brake shoes (as the rear wheel is missing due to the cassette trainer, we used a 3D-printed component). Via the microcontroller, the measured brake pressure is forwarded to the resistance control of the smart trainer.

To support the tilting function, we used a Next Level Racing Motion Platform V3[4], which is typically used for racing games and (home) flight simulators. The platform allows tilting up to 10 degrees in both lateral and longitudinal axes (maximum speed $20°/s$, maximum acceleration $360°/s^2$). Our initial implementation does not support the pitch function (leaning forwards/backwards) that we will investigate in future experiments. Controlling the platform is supported via a Unity SDK provided by the manufacturer. To further increase the realism, as suggested by related works, we added an airstream simulation with a tubular fan placed directly in front of a rider's face. The fan starts to operate at a measured cycling speed of 10km/h and runs at full force at (and above) 20km/h. The data of all components is transferred to a microcontroller (Arduino), which is connected to a Unity3D environment via USB. To stabilize the whole simulator, we mounted it on an aluminum frame. As a VR device, we chose the Oculus Quest 2 with a resolution of 1832x1920 per eye.

Fig. 2. Left: Overview of components used to build the bicycle simulator. Right: Virtual environment used for evaluation.

[4]https://nextlevelracing.com/products/next-level-racing-motion-platform-v3

3.1 Simulator Tilt Modes

To develop the tilt support of the simulator, we conducted a field study with a real bicycle. According to [4, 67], the tilt angle α of a bicycle can be calculated as a function of the bike's velocity (v), the curve radius r, and the earth's gravity (g), see Equation 1. The tilt angles should be independent of rider characteristics. However, we wanted to compare and validate the physics model with the recorded data. We mounted an Arduino Nano 33 BLE Sense on the carrier of a bicycle and used the built-in accelerometer and the gyroscope to record the (maximum) tilt angle in curves. Additionally, we used the potentiometer as described above to record the steering angle. We used chalk to draw uniform curves (2.5, 5, 10, and 15m radius) onto a concrete area and let two cyclists follow the trajectories with different initial speeds when entering the curves (10, 15, 20, and 25km/h, see Figure 3). Both cyclists are experienced and frequent riders who cycle around 1500km per year (on average, without commutes). The measurements were started/stopped with a button mounted on the handlebar, and the cyclists monitored their speed with GPS. Because of safety reasons, the smallest curve (2.5m radius) was only recorded at 10 and 15km/h. Both cyclists drove each combination of curve radius and speed twice. The results are, together with the tilting angles calculated by the formula given in [4] depicted in Table 2.

radius[m]	velocity[km/h]	max steering angle[°]	max tilt[°]	calc. tilt[°]	*strong* tilt[°]	*weak* tilt[°]
2,5	10	38,96	11,28	17,46	2.18	0.99
2,5	15	29,55	24,94	35,29	4.41	1.93
5	10	24,18	5,91	8,94	1.12	0.50
5	15	22,84	14,68	19,49	2.44	0.99
5	20	14,78	18,18	32,18	4.02	1.59
5	25	17,46	21,94	44,51	5.00	2.28
10	10	12,09	2,09	4,50	0.56	0.25
10	15	14,78	6,09	10,04	1.25	0.49
10	20	14,78	13,21	17,46	2.18	0.80
10	25	14,78	20,27	26,18	3.27	1.17
15	10	12,09	1,44	3,00	0.38	0.17
15	15	10,75	3,87	6,73	0.84	0.33
15	20	10,75	9,35	11,85	1.48	0.54
15	25	18,81	14,98	18,15	2.27	0.78

Table 2. Results of the curve characteristics measurements show that the recorded tilt angles slightly below the values given by the physics model. The two rightmost columns show the final tilt values after mapping the tilt function outputs to the platform.

The results show that the recorded tilt angles are (in most cases) smaller than the ones given by the calculations. However, since we observed a large variance in the measurements and as it is known that accelerometer and gyroscope measurements can be unstable [4], we decided to rely on the formula for calculating the *strong* tilt mode for the simulation.

To realize the tilt, we tried out different variants tested by the same two cyclists as in the field study above on the simulator. First, we implemented the formula as is (Equation 1, left) and utilized the full 10° tilt of the platform (i.e., all tilt angles above 10° are cut off, remaining at 10° maximum). We quickly realized that this solution was unmanageable for riders due to the strong and fast changes, even when cycling relatively slow. For example, steering from a left-hand curve to a right-hand curve with a 10m radius with only 15km/h would instantly tilt the platform from −10°

to +10°, which induced strong motion sickness given that no centrifugal force compensates for the feeling of "falling from left to right". Consequently, we tried another variant, where we defined the maximum 10° tilt angle of the platform to represent a potentially strong tilt as given by our measurements. Since the curve with a 5m radius and 25km/h was already perceived as dangerous and unnatural for the cyclists on the test track (i.e., 44.51°, see Table 2), we decided to map the maximum tilt of the platform to 40° in reality. All tilt angles (between 0° and 40°) as given by the physics model were linearly mapped to the 0° to 10° of the platform. The resulting behavior was still perceived as too strong, as a platform tilt around 10° created a leverage effect (i.e., perception of falling over). Therefore, we implemented an even more conservative solution by mapping the results of the physics model to only −5° to +5° of the platform tilt. The translated tilt values of this mode can be seen in Table 2 (*strong* tilt).

However, despite the introduced changes, the tilting behavior still appeared too strong and uncomfortable. We realized that this perception was not necessarily depending on the tilt angles themselves but rather on the dynamic behavior when slightly adjusting the handlebar. At a speed of 20km/h, even minimal handlebar adjustments made the platform tilt from one side to the other. Thus, we decided to include an even more conservative condition for our evaluation. We applied a heuristic approach and experimented with the parameters of the tilt function to achieve a behavior that results in less aggressive onset when dynamically adjusting the handlebar. The resulting *weak* function (Equation 1 right) leads to similar but less steep tilt with increasing speed (see Figure 3). The final platform tilt values of the *weak* tilt mode are depicted in the rightmost column in Table 2. The values appear small, but we were surprised how well even these slight movements (in the range of −2.28° to 2.28°) created a convincing illusion of "cycling in VR". With these changes, we aimed to reduce motion sickness and the increase realism of cycling in our VR simulator.

$$\alpha_{strong} = \arctan(\frac{v^2}{g * r}) \qquad \alpha_{weak} = \arctan(\frac{0.6 * v^{1.7}}{g * r}) \tag{1}$$

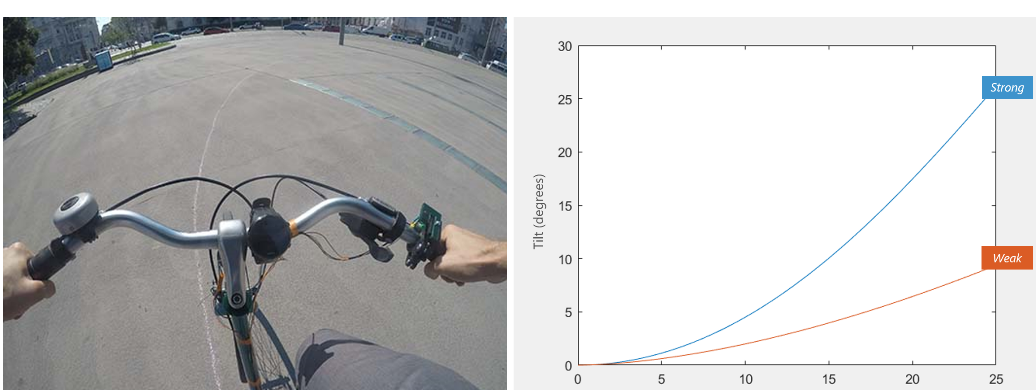

Fig. 3. Left: Systematic recording of the tilt angles for different curve radii and speeds; Right: tilt angle for a curve with a radius of 10m as a function of speed, where the *weak* tilt mode (orange) is downscaled in comparison to the physically accurate calculation (blue). The final values were then mapped to the platform range of -5° to +5°.

3.2 VR Test Environment

To allow a comparative evaluation of the different tilt modes, we created a small city environment in Unity3D. We built Unity prefabs of 90° two-lane road curves with the same radii as used in the pilot study described above and created a closed-loop (17 curves, 4x 2.5m, 4x 5m, 4x 10m, and 5x 15m, approximately 2 minutes duration for a single lap, see Figure 2). We placed 127 semi-transparent spheres equally distant from each other to indicate the ideal trajectory that study participants should follow. To allow for a more realistic environment, we placed trees, lights, benches, and other urban objects in the scenery. Additionally, we created another environment in the form of a large parking area, i.e., a quadratic plane without any obstacles, to facilitate participants' accommodation and experimentation with the different tilting modes. The visual tilt in the VR headset was adjusted 1:1 to the simulator tilt, i.e., we did not induce a larger visual tilt angle to reduce the number of influencing parameters.

4 USER STUDY

We set up a controlled lab study where we varied the tilt mode as an independent variable with the three conditions *strong* tilt (as given by the physics model), *weak* tilt (function with less aggressive onset as described above), and *baseline* (static simulation without tilt). Participants completed the test track three times, once with each tilt mode (within-subjects design). With this experiment, we aimed to answer the following research questions (RQs):

- **RQ1:** How much can a bicycle simulator's tilt function increase a potentially realistic perception of cycling in virtual reality ("presence") compared to a static simulator?
- **RQ2:** How much does a tilt function of a bicycle simulator influence simulator sickness, compared to a static simulator?
- **RQ3:** How much does a tilt function of a bicycle simulator influence cycling performance in virtual reality, compared to a static simulator?

4.1 Measurements

To answer our RQs, we included a set of quantitative and qualitative measurements to assess simulator sickness, perceived realism/presence, user experience, as well as driving performance.

4.1.1 Self-Ratings. Perceived realism/presence in VR was assessed with the Ingroup Presence Questionnaire [50] that measures three dimensions spatial presence (sense of being in the virtual environment), involvement (attention given to the virtual environment), and experienced realism (presence in the virtual environment; 14 items on a 6-point Likert scale from 0 to 6). To investigate motion sickness, we included the simulator sickness questionnaire (SSQ), which consists of 16 items (rated on a 4-point Likert scale from 0 to 3) in the three dimensions of nausea, oculomotor, and disorientation [23]. To quantify UX, we utilized the short version of the User Experience Questionnaire (UEQ-S) [49], which consists of 8 items (7-point Likert scale from -3 to +3) in the two dimensions of pragmatic and hedonic quality.

4.1.2 Driving Performance. To assess how well participants could cycle through the test track, we quantified their lane-keeping performance and speed. Both parameters were calculated based on the cyclists passing the semi-transparent spheres (i.e., the discrete measurement points). We utilized the Standard Deviation of Lateral Position (SDLP, deviation of the handle bar's minimal distances to the spheres' center points), which is a frequently used performance parameter in traffic safety experiments [24]. The exact moment when the SDLP was calculated (i.e., minimal distance to the sphere center point) was also used to record the cyclists' average speed (km/h).

In addition to these measurements, participants were emphasized to express their experience in a short semi-structured interview, where we asked them to reflect on the advantages and disadvantages of the conditions and rank them according to their personal preferences.

4.2 Participants and Procedure

In total, 31 participants (21 male, 10 female; aged between 22 and 42; M=30.93, SD=5.54 years; mostly students and university staff) completed the experiment. Most (>90%) had no or just rare experience with VR technology. 3 participants ride bicycles daily, 6 multiple times per week, 7 multiple times a month, 12 occasionally, and 3 participants stated being able to ride but typically not using bicycles in their daily life. No participant showed signs of simulator sickness before the onset of the study. Two (additional) participants, who were not included in this evaluation due to missing data, stopped participating because of simulator sickness.

Upon appearance, participants expressed written consent and completed a questionnaire addressing demographics, cycling and VR experience, and the SSQ (pre-test). Then, we briefed them about the study, and they could get familiar with the simulator. Before experiencing each of the three experimental conditions (*strong* and *weak* tilt, as well as the *baseline* condition without tilting), we placed them in a separate VR environment (a large parking lot without obstacles) to accommodate with the corresponding simulator behavior. As soon as they stated to be ready for the test drive, they completed the test track before completing the post-condition surveys with the scales as described above. The order of the conditions *weak* tilt and *baseline* was counterbalanced, but all participants completed the *strong* tilt condition at the end. We chose this procedure as we feared dropouts, i.e., experiencing the condition with the most simulator motion could make some participants stop the experiment. After all three conditions, we performed the post-test interview. The study duration was about 30-45 minutes per participant and was conducted according to the University's precautions regarding the COVID-19 pandemic.

4.3 Results

We utilized IBM SPSS to evaluate the recorded data, where all investigated scales showed acceptable reliability (Cronbach's $\alpha > .6$). Consequently, we were able to calculate scale values. We performed analyses of variance (ANOVAs), and Friedman tests (if tests for normality failed; both were reported as statistically significant at $p < .05$). In case the Friedman test yielded a significant result, subsequent pairwise comparisons (Wilcoxon post-hoc tests) were conducted with a Bonferroni-corrected significance threshold of $.01\overline{6}$. Descriptive statistics of the SSQ results are depicted in Table 3, and we also report the medians (Med) and Interquartile Ranges (IQR) if a Friedman test had to be conducted.

4.3.1 Immersion and Perceived Realism. The *weak* tilt mode received the highest ratings in all sub-scales of the IPQ, followed by the *baseline* and the *strong* tilt.

The Friedman test indicated a significant effect for the **spatial presence** dimension (*baseline* Med=4.4 IQR=3.8-4.9, *weak* Med=4.6 IQR=4.1-5.2, *strong* Med=4.2 IQR=3.3-4.7; $\chi^2(2) = 10.352, p = .006$), whereas post-hoc tests revealed that the *weak* tilt showed significantly higher spatial presence than the *strong* tilt mode ($Z = -3.087, p = .002$). Other comparisons in this dimension failed to meet the significance level.

While there were no differences revealed for **involvement** (*baseline* Med=3.75 IQR=2.8-4.3, *weak* Med=4 IQR=3.5-4.6, *strong* Med=3.5 IQR=2.1-4.3), a significant effect was also present for the dimension of **experienced realism** (*baseline* Med=2.3 IQR=1.6-2.9, *weak* Med=2.8 IQR=2.3-3.4, *strong* Med=2.3 IQR=1.8-2.9; $\chi^2(2) = 11.450, p = .003$). Results of the subsequent pairwise comparisons showed that the *baseline* and the *strong* tilt are perceived similarly realistic, while the *weak* tilt

	Baseline M (SD)	Strong Tilt M (SD)	Weak Tilt M (SD)
Ingroup Presence Questionnaire - IPQ			
Spatial Presence	4.38 (0.86)	3.95 (1.11)	4.60 (0.91)
Involvement	3.68 (1.26)	3.31 (1.42)	3.91 (1.01)
Experienced Realism	2.30 (0.80)	2.21 (0.89)	2.72 (0.76)
Simulator Sickness Questionnaire - SSQ			
Total	23.3 (26.1)	40.8 (38.1)	21.5 (22.1)
Nausea	21,7 (29.4)	42.4 (42.6)	23.7 (29.0)
Oculomotor	16.5 (14.5)	25.1 (22.1)	15.7 (13.9)
Disorientation	25.0 (35.2)	43.7 (51.1)	16.8 (21.2)
User Experience Questionnaire - UEQ-S			
Pragmatic Quality	1.93 (0.81)	0.51 (1.57)	1.91 (0.65)
Hedonic Quality	2.11 (0.95)	2.18 (0.88)	2.35 (0.67)
Driving Performance Measurements			
SDLP	0.094 (0.051)	0.127 (0.066)	0.110 (0.051)
Mean Velocity (km/h)	11.19 (2.08)	9.21 (1.61)	11.04 (2.30)

Table 3. Descriptive Statistics (mean M and standard deviation SD) for the assessed self-rating scales and driving performance measures.

mode was perceived as significantly more realistic than both the *strong* tilt ($Z = -2.855, p = .004$) and the *baseline* condition ($Z = -2.601, p = .009$), see Figure 4.

4.3.2 User Experience Questionnaire. Similar results could be obtained for the UEQ-S. The *baseline* and the *weak* tilt mode received comparably high ratings for **pragmatic quality**, while the *strong* tilt was rated lower. The difference was statistically significant ($\chi^2(2) = 23.57, p < .001$). Pairwise comparisons confirm that both the *baseline* (Med=2.0, IQR=1.3-2.8, $Z = -4.336, p < .01$) and the *weak* (Med=1.75, IQR=1.5-2.4, $Z = -4.088, p < .01$) tilt were rated significantly better than the *strong* tilt (Med=0.8, IQR=-0.8-1.5), while there was no difference between the *weak* tilt and the *baseline*. Regarding the dimension of **hedonic quality**, no significant effect was indicated as all conditions received similar ratings.

4.3.3 Simulator Sickness. The *strong* tilt mode led to the strongest simulator sickness, while the *weak* tilt mode showed similar results to the *baseline* (for the total score and across all SSQ dimensions).

Considering the **total SSQ score** (the combination of the three sub-dimensions), a statistically significant difference was indicated (*baseline* Med=15.0 IQR=7.5-31.8, *weak* Med=15.0 IQR=7.5-30.0, *strong* Med=29.9 IQR=11.2-63.6; $\chi^2(2) = 23.703, p < .001$). Post-hoc comparisons reveal significant differences between the *baseline* condition and the *strong* tilt ($Z = -3.612, p < .001$), as well as between the *strong* and the *weak* tilt ($Z = -3.894, p < .001$), while no differences were present between the *baseline* and the *weak* tilt condition. Regarding the **nausea** dimension, the Friedman test yielded a significant effect (*baseline* Med=9.5 IQR=0-28.6, *weak* Med=19.1 IQR=9.5-28.6, *strong* Med=28.6 IQR=9.5-57.2; $\chi^2(2) = 16.247, p < .001$). Pairwise comparisons showed that there was no significant difference between the *baseline* and the *weak* tilt, while the differences between the *baseline* and the *strong* ($Z = -3, 449, p < .001$), as well as the *strong* and the *weak* condition were significant ($Z = -3.627, p < .001$). We observed the same pattern for the other two dimensions.

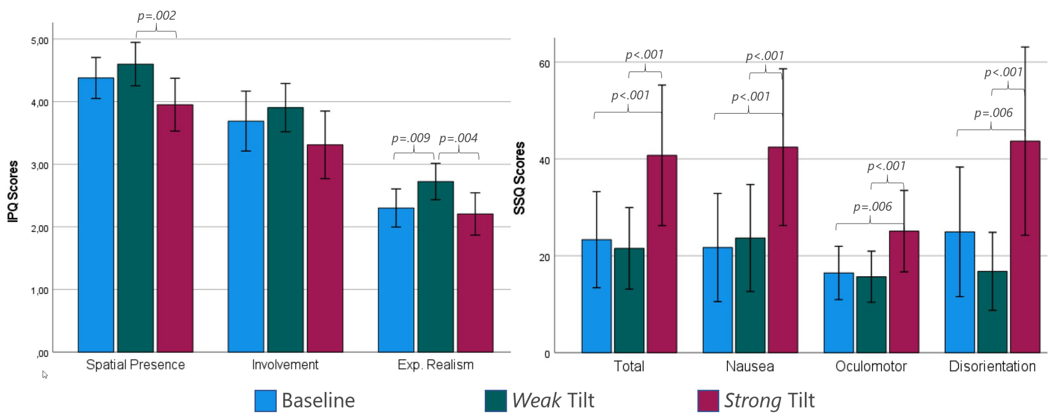

Fig. 4. According to the results of the IPQ scale, the *weak* tilt mode resulted in the highest ratings in all dimensions and provided the most realistic experience (left). Regarding the SSQ results, the *strong* tilt yielded significantly higher sickness than the other two conditions (right).

Regarding the **oculomotor** dimension (*baseline* Med=15.2 IQR=7.6-22.7, *weak* Med=7.6 IQR=7.6-22.8, *strong* Med=15.6 IQR=7.6-38.0; $\chi^2(2) = 13.229, p < .001$), there was also no difference between the *baseline* and the *weak* tilt, while the differences between *baseline* and *strong* ($Z = -2,764, p = .006$), as well as *weak* and *strong* conditions ($Z = -3.446, p < .001$) were statistically significant. Finally, the **disorientation** dimension shows a similar result (*baseline* Med=13.9 IQR=0-27.8, *weak* Med=13.9 IQR=0-27.8, *strong* Med=27.8 IQR=7.0-62.6; $\chi^2(2) = 14.237, p < .001$). Only the differences between *baseline* and *strong* ($Z = -2,76, p = .006$), as well as *weak* and *strong* conditions ($Z = -3.402, p < .001$) were statistically significant.

4.3.4 Driving Performance Measures. To investigate participants' cycling behavior, we evaluated the standard deviation of lateral position and their speed. The potentially "best" driving performance (i.e., highest speed and lowest lane deviation) was achieved in the *baseline* condition, followed by the *weak* (slightly lower) and the *strong* tilt (significantly lower) modes. Since the data were normally distributed, we conducted parametric repeated measures ANOVAs (assumptions for sphericity not met). Considering the **standard deviation of lateral position**, a significant effect was indicated (Greenhouse-Geisser, $F(1.797, 50.307) = 4.701, p = .016$). Post-hoc comparisons showed that in the *strong* tilt, participants' lane-keeping performance was significantly worse than in the *baseline* condition ($p = .021$).
A significant effect was also visible for the mean **speed** (Greenhouse-Geisser, $F(1.897, 53.118) = 23.069, p < .001$). Participants drove significantly slower in the *strong* tilt mode than in both the other conditions *weak* tilt ($p < .001$) and *baseline* ($p < .001$). No other comparisons indicated significance.

4.3.5 Semi-Structured Interviews. In the interviews, we asked participants (2 had to be excluded because of damaged audio recordings) to express which of the three experimental conditions (i.e., tilt modes) they liked the most and which they liked the least, as well as to justify their decision to uncover the "why" (see Figure 5). 15 (out of 31) participants preferred the *weak* tilting mode. Eight of them justified their preference with the right amount of realism. Three participants stated that the reason for the preference was due to the presence of movement, while 2 explicitly mentioned that *"it moves, but not too extreme"*. Six participants preferred the *baseline* condition because, for them, it was easy and felt *"like a game"*. In contrast, five other participants preferred the *strong* tilt mode,

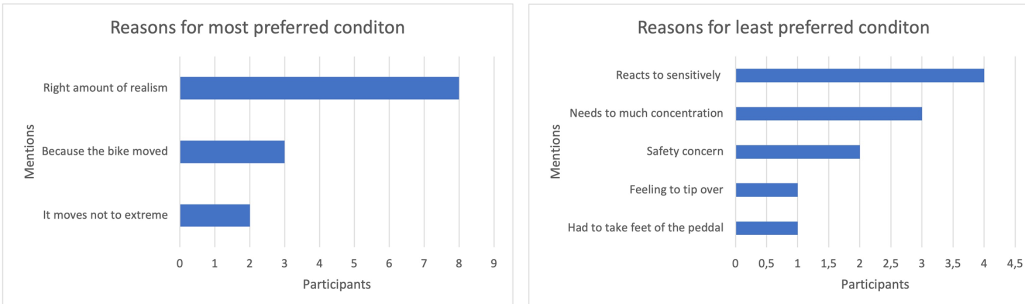

Fig. 5. Participants expressed different reasons for their rankings of the most and least preferred experimental condition (those do not belong to a particular condition, see Section 4.3.5).

where two of them justified their choice because they had to concentrate the most, while another participant liked it because it was challenging. The remaining participants could not identify a favorite.

Regarding the least preferred cycling tilt, 16 participants chose the *strong* condition, where four argued that it reacts too sensitively to their actions and had too much movement. Two participants argued with safety concerns, and another one argued that it felt like they would constantly *"tip over"*. Seven participants disliked the *baseline* most, where a common reason expressed by 7 participants was the lack of movement, making the simulator unrealistic and boring. Four participants disliked the *weak* tilt mode because it does neither feel very realistic nor like a video game.

5 DISCUSSION

Our results demonstrate that platform tilt plays a vital role in the perception of cycling in virtual reality. However, it requires careful consideration when designing VR bicycle simulators. Overall, the results of our experiment show that simulator tilt can positively affect humans' perception of cycling in virtual reality, but only when the tilt angles are moderate – it was surprising to see how small tilting angles in a range of only $-2.28°$ to $+2.28°$ can improve the experience. Stronger tilting angles, in contrast, degrade cycling performance and immersion, which leads to higher motion sickness. This indicates that there exists a "sweet spot" for a tilting function that balances the involved concepts of performance, perception, and simulator sickness. Still, the *weak* function as used in this experiment should not be considered a best practice or reference value, as its parameters were based only on a small pilot study with two cyclists. Additionally, it should be mentioned that the main problem of the *strong* tilt mode seems to mainly stem from the fast dynamic adjustments of the handlebar that are immediately reflected by the platform, rather than the maximum tilt values in the curves. Further improvements and a systematic investigation are necessary to improve cycling in VR simulators. Moreover, given that simulator sickness in VR cycling is influenced by varying driving scenarios [40], therefore it is necessary to determine the optimal tilting behavior for different movements, i.e., cycling upwards/downwards, turning at different angles, or different speeds. This leads to the question of how much tilt should be applied in particular situations. Still, we can confirm that the inclusion of a moderate tilt function (which should be carefully designed to balance between simulator sickness and immersive experiences) can convey a realistic cycling experience for human users, which is particularly relevant if the intended driving scenarios contain curvy trajectories. We investigated the influence of the tilting function on realism, user experience, motion sickness, and cycling performance, which we discuss in detail in the following.

5.1 How does Tilting influence Presence and User Experience?

We compared the two modes of a *strong* tilt and a *weak* tilt with a less aggressive onset to a baseline without any motion. Thereby, the *weak* tilt mode was rated as the most realistic. It was ranked highest in all dimensions of the IPQ scale and rated significantly higher than the other two conditions in terms of "perceived realism". The statistical evaluation was also supported by the semi-structured interviews, where the *weak* tilt mode was the one most preferred by study participants for reasons such as showing *"the right amount of realism"*. In contrast, the *strong* tilt mode was rated worst across all dimensions and also the least preferred condition among study participants. The IPQ ratings show that this mode could not improve the immersion or perceived realism compared to the *baseline*, which even was rated slightly higher in all sub-scales (although the differences are not significant). Consequently, we can confirm that a tilt function can significantly increase a realistic perception of cycling in virtual reality, but only when the tilt function reacts less extreme to the changing speed and curve radii (**RQ1**). We evaluated similar results regarding user experience. In the UEQ-S, the *baseline* and *weak* tilt scored similar, while the *strong* tilt led to significantly lower pragmatic quality. Regarding hedonic quality, all conditions were rated similarly, potentially as the bicycle simulator was a novel experience for our participants in general.

5.2 How does Tilting influence Motion Sickness?

The *strong* tilt significantly worsened the situation from the perspective of simulator sickness. In the SSQ total score as well as all sub-scales, the *strong* tilt mode resulted in significantly more sickness than the other two conditions. The *weak* tilt, in turn, was rated similar to the *baseline* condition, according to the total SSQ score and its sub-scales. In summary, even a downscaled tilt function for a bicycle simulator can worsen simulator sickness when reflecting a realistic relationship of speed and curve radius (i.e., tilt onset following small handlebar adjustments), while a weak and minor tilt mode does at least not yield to more sickness than a static simulation (**RQ2**). However, the results must also be interpreted with caution as simulator sickness can increase due to carry-over effects, and our participants completed the *strong* tilt mode always in the end. We argue that the large differences (see Figure 4) would not suggest that the observed differences stem mainly from such carry-over effects. Still, we hypothesized that an adequately applied tilt mode would not only benefit perceived realism but simulator sickness too since Weech et al. [63] have argued that "both factors may be manipulated with a single approach". So what could be the reasons that simulator sickness did not decrease although perceived realism improved? Even though both constructs are based on a match/mismatch of sensory perception, additional interventions can "generate both a compelling sense of 'being there', and symptoms of physiological discomfort" [63]. Maybe a better parameterized tilting function could lead to the desired effect. However, it could also mean that even more and better interventions are required to eliminate all the sensory conflicts when cycling in VR. This could include: (1) a combination of handlebar steering and weight shifts input since both contribute to cycling dynamics [25], (2) a force rather than a tilt simulation, which calculates the superimposition of the centrifugal force and the downforce to adjust the bike movement accordingly, or (3) an additional rotatable platform that can produce centrifugal forces. Finally, training and habituation effects could benefit the situation. Longer phases of adaptation have shown to reduce simulator sickness for vehicle [9] and scooter [20] simulators, which we aim to address in future studies where participants are exposed to the different tilt modes longer and more frequently.

5.3 Cycling Performance versus Tilt

The simulator tilt significantly influenced the cycling performance of participants. Similar to simulator sickness, the *strong* tilt led to the worst performance. It significantly increases the standard deviation of lateral position compared to the *baseline*, which can be interpreted in a way that study participants could not follow the intended trajectory very accurately. Also, the mean velocity with the *strong* tilt mode was significantly lower than in the other two conditions. We are inclined to use the term "worsened" here as we compare the speed to the 13.6km/h that has been determined as the average velocity in natural environments by Dozza and Fernandez [11]. Using the *weak* tilt, participants' speed and lane deviation were slightly (but not significantly) worse than the *baseline*. To summarize, similar to the simulator sickness, a tilting mode for a VR bicycle simulator leads to decreased cycling performance when the tilt angle is too strong, while moderate tilting results in a similar performance to a static simulation without motion (**RQ3**).

6 LIMITATIONS AND FUTURE WORK

We observed several technical limitations of the designed bicycle simulator and the experimental evaluation, which should be considered in future projects. First, similarly to many other bike simulators, it was only possible to drive curves using a handlebar rotation, while in reality, driving curves is achieved via a combination of steering movements and weight shifts, i.e., "leaning into the curve". Thus, we plan to include pressure sensors similar to [8] in the future so that the simulator can recognize and react to such movements of the rider. A combination of handlebar steering and body positioning could be an interesting aspect of future studies: The study conducted by Matviienko et al. [40] has shown that handlebar steering is less degrading (in terms of simulator sickness) than body movements. In contrast, the evaluation by Westerhof et al. [66] in the motorcycle domain suggested that adding body positioning to traditional steering can reduce simulator sickness (i.e., both results are not necessarily contradictory). Second, as already discussed, the bicycle simulator's motion platform simulates bike tilt rather than forces. One can think of the forces that would apply to a rider when entering a curve: At the onset of the curve, i.e., when leaning into it, a realistic force simulation would indeed result in a tilt, which is then quickly superimposed by the centrifugal force. A force-based motion simulator could mimic this effect by tilting the bike up again during the curve so that the rider would only feel the downforce while still seeing a tilted view in the virtual world. Another possibility could be to mount the entire simulator on a rotatable platform to be able to generate the required centrifugal force. However, motorcycle simulators also typically simulate tilt rather than correct physical forces [3]. One reason for this could be that in the past, many simulators for two-wheeled vehicles were limited to screens rather than VR, where an exact force simulation creates a conflict with the orientation of the real and the virtual world. VR glasses can eliminate this issue [66] and allow more realistic force simulations. Additionally, we aim to improve other simulation elements, such as brakes, audio, and improvement of the visual environment. Finally, with our work, we aimed to improve the VR cycling experience by reducing motion sickness and increasing realism, but due to the limited sample size and different cultural backgrounds of the participants, and short exposure to the individual conditions, generalizing our results to a larger group of cyclists might be difficult, which would require further experiments in the future.

7 CONCLUSION

In this paper, we have investigated how a tilt function for a virtual reality bicycle simulator affects perceived realism, simulator sickness, and cycling performance. We installed a bicycle simulator on a motion platform (without rotational motion) and implemented two characteristic tilting modes for evaluation – a *strong* tilt mode, which follows a downscaled version of a physics model for bicycle dynamics, and an improved *weak* tilt with less aggressive onset by adjusting the function parameters. Both tilting functions were mapped to a range of $-5°$ to $+5°$ of the motion platform and compared to a static baseline condition without motion in a user study with 31 participants. The results show that the *strong* tilt degrades presence, cycling performance, and simulator sickness. The *weak* tilt mode, in contrast, could significantly improve the subjectively perceived realism without worsening cycling performance and simulator sickness. Summarized, our research demonstrates that even very slight tilting can have a beneficial effect and suggests that there exists a sweet spot for a tilting function that can balance between presence/immersion and simulator sickness. Beyond the evaluated experimental results, we contribute to the design of high-fidelity bicycle simulators by discussing additional interventions that could help to provide more realistic cycling experiences in the future.

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REFERENCES

[1] Josh Andres, Julian de Hoog, and Florian 'Floyd' Mueller. 2018. "I Had Super-Powers When EBike Riding" Towards Understanding the Design of Integrated Exertion. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play* (Melbourne, VIC, Australia) *(CHI PLAY '18)*. Association for Computing Machinery, New York, NY, USA, 19–31. https://doi.org/10.1145/3242671.3242688

[2] 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). https://doi.org/10.3389/fneur.2020.614664

[3] Simone Benedetto, Régis Lobjois, Vérane Faure, Nguyen-Thong Dang, Marco Pedrotti, and Stéphane Caro. 2014. A comparison of immersive and interactive motorcycle simulator configurations. *Transportation Research Part F: Traffic Psychology and Behaviour* 23 (2014), 88–100. https://doi.org/10.1016/j.trf.2013.12.020

[4] Carsten Bielmeier. 2012. Thema: Fahrradphysik.

[5] Greg Byrd. 2015. Cycling through Cyberspace. *Computer* 48, 8 (2015), 72–75. https://doi.org/10.1109/MC.2015.220

[6] 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 arXiv:https://doi.org/10.1080/10447318.2020.1778351

[7] 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

[8] Raphael de Souza e Almeida, Renato Cherullo, Daniel Radetic, Greis Francy M. Silva-Calpa, and Alberto Barbosa Raposo. 2019. Exploring Motor and Sensory Devices in a Bicycle Simulator. In *2019 21st Symposium on Virtual and Augmented Reality (SVR)*. IEEE, Rio de Janeiro, Brazil, 232–241. https://doi.org/10.1109/SVR.2019.00048

[9] Joshua E. Domeyer, Nicholas D. Cassavaugh, and Richard W. Backs. 2013. The use of adaptation to reduce simulator sickness in driving assessment and research. *Accident Analysis & Prevention* 53 (2013), 127–132. https://doi.org/10.1016/j.aap.2012.12.039

[10] L. Dominjon, A. Lecuyer, J.-M. Burkhardt, P. Richard, and S. Richir. 2005. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* IEEE, Bonn, Germany, 19–25. https://doi.org/10.1109/VR.2005.1492749

[11] Marco Dozza and Andre Fernandez. 2014. Understanding Bicycle Dynamics and Cyclist Behavior From Naturalistic Field Data (November 2012). *IEEE Transactions on Intelligent Transportation Systems* 15, 1 (2014), 376–384. https://doi.org/10.1109/TITS.2013.2279687

[12] 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

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

[14] 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

[15] Ayah Hamad. 2021. *Two Wheelistic: Development of a High-Fidelity Virtual Reality Cycling Simulator for Transportation Safety Research.* Ph. D. Dissertation. University of Michigan-Dearborn.

[16] 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

[17] G. Hernández–Melgarejo, D.A. Flores–Hernández, A. Luviano–Juárez, L.A. Castañeda, I. Chairez, and S. Di Gennaro. 2020. Mechatronic design and implementation of a bicycle virtual reality system. *ISA Transactions* 97 (2020), 336–351. https://doi.org/10.1016/j.isatra.2019.08.002

[18] 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

[19] 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

[20] Joost Heutink, Minou Broekman, Karel A. Brookhuis, Bart J. M. Melis-Dankers, and Christina Cordes. 2019. The effects of habituation and adding a rest-frame on experienced simulator sickness in an advanced mobility scooter driving simulator. *Ergonomics* 62, 1 (2019), 65–75. https://doi.org/10.1080/00140139.2018.1518543 arXiv:https://doi.org/10.1080/00140139.2018.1518543 PMID: 30185112.

[21] 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*. IEEE, Shanghai, China, 2567–2570. https://doi.org/10.1109/IEMBS.2005.1616993

[22] Heather Kaths, Andreas Keler, Jakob Kaths, and Fritz Busch. 2019. Analyzing the behavior of bicyclists using a bicycle simulator with a coupled SUMO and DYNA4 simulated environment. , 199–205 pages.

[23] 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

[24] Gwendolin Knappe, Andreas Keinath, Klaus Bengler, and Cristina Meinecke. 2007. Driving simulator as an evaluation tool–assessment of the influence of field of view and secondary tasks on lane keeping and steering performance.

[25] J.D.G. Kooijman and A.L. Schwab. 2013. A review on bicycle and motorcycle rider control with a perspective on handling qualities. *Vehicle System Dynamics* 51, 11 (2013), 1722–1764. https://doi.org/10.1080/00423114.2013.824990 arXiv:https://doi.org/10.1080/00423114.2013.824990

[26] Thomas Kosch, Andrii Matviienko, Florian Müller, Jessica Bersch, Christopher Katins, Dominik Schön, and Max Mühlhäuser. 2022. NotiBike: Assessing Target Selection Techniques for Cyclist Notifications in Augmented Reality. In *Proceedings of the 24th international conference on human-computer interaction with mobile devices and services (MobileHCI '22)*. ACM, New York, NY, USA. https://doi.org/10.1145/3546732

[27] 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

[28] 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

[29] 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

[30] 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

[31] 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.* IEEE, Bonn, Germany, 289–290. https://doi.org/10.1109/VR.2005.1492799

[32] 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

[33] 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

[34] Andrii Matviienko, Swamy Ananthanarayan, Abdallah El Ali, Wilko Heuten, and Susanne Boll. 2019. *NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300850

[35] Andrii Matviienko, Swamy Ananthanarayan, Raphael Kappes, Wilko Heuten, and Susanne Boll. 2020. Reminding Child Cyclists about Safety Gestures. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays* (Manchester, United Kingdom) *(PerDis '20)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3393712.3394120

[36] Andrii Matviienko, Florian Heller, and Bastian Pfleging. 2021. Quantified Cycling Safety: Towards a Mobile Sensing Platform to Understand Perceived Safety of Cyclists. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 262, 6 pages. https://doi.org/10.1145/3411763.3451678

[37] Andrii Matviienko, Wilko Heuten, Alan Dix, and Susanne CJ Boll. 2021. Interactive Technology for Cycling — Ideate, Make – Remote, Together. In *Adjunct Publication of the 23rd International Conference on Mobile Human-Computer Interaction*. Association for Computing Machinery, New York, NY, USA, Article 29, 4 pages. https://doi.org/10.1145/3447527.3474870

[38] Andrii Matviienko, Damir Mehmedovic, Florian Müller, and Max Mühlhäuser. 2022. "Baby, You can Ride my Bike": Exploring Maneuver Indications of Self-Driving Bicycles using a Tandem Simulator. In *Proceedings of the 24th International Conference on Mobile Human-Computer Interaction* (Vancouver, Canada) *(MobileHCI '22)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3546723

[39] Andrii Matviienko, Florian Müller, Dominik Schön, Paul Seesemann, Sebastian Günther, and Max Mühlhäuser. 2022. BikeAR: Understanding Cyclists' Crossing Decision-Making at Uncontrolled Intersections Using Augmented Reality. In *CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 366, 15 pages. https://doi.org/10.1145/3491102.3517560

[40] Andrii Matviienko, Florian Müller, Marcel Zickler, Lisa Alina Gasche, Julia Abels, Till Steinert, and Max Mühlhäuser. 2022. Reducing Virtual Reality Sickness for Cyclists in VR Bicycle Simulators. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 187, 14 pages. https://doi.org/10.1145/3491102.3501959

[41] Miguel Melo, Tânia Rocha, Luís Barbosa, and Maximino Bessa. 2016. Presence in virtual environments: Objective metrics vs. subjective metrics — A pilot study. In *2016 23rd Portuguese Meeting on Computer Graphics and Interaction (EPCGI)*. IEEE, Guimarães, Portugal, 1–6. https://doi.org/10.1109/EPCGI.2016.7851200

[42] 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

[43] M. Nazemi, M.A.B. van Eggermond, A. Erath, D. Schaffner, M. Joos, and Kay W. Axhausen. 2021. Studying bicyclists' perceived level of safety using a bicycle simulator combined with immersive virtual reality. *Accident Analysis & Prevention* 151 (2021), 105943. https://doi.org/10.1016/j.aap.2020.105943

[44] 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

[45] 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

[46] 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

[47] 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

[48] Gian-Luca Savino, Tamara von Sawitzky, Andrii Matviienko, Miriam Sturdee, Paweł W. Woźniak, Markus Löchtefeld, Andrew L. Kun, Andreas Riener, and Jonna Häkkilä. 2021. Cycling@CHI: Towards a Research Agenda for HCI in the

Bike Lane. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 107, 5 pages. https://doi.org/10.1145/3411763.3441316

[49] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2017. Design and evaluation of a short version of the user experience questionnaire (UEQ-S). *International Journal of Interactive Multimedia and Artificial Intelligence, 4 (6), 103-108.* 6, 4 (2017), 103–108.

[50] Thomas W Schubert. 2003. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. *Z. für Medienpsychologie* 15, 2 (2003), 69–71.

[51] Amit Shahar, Virginie Dagonneau, Séphane Caro, Isabelle Israël, and Régis Lobjois. 2014. Towards identifying the roll motion parameters of a motorcycle simulator. *Applied Ergonomics* 45, 3 (2014), 734–740. https://doi.org/10.1016/j.apergo.2013.09.013

[52] Murad M. Shoman and Hocine Imine. 2021. Bicycle Simulator Improvement and Validation. *IEEE Access* 9 (2021), 55063–55076. https://doi.org/10.1109/ACCESS.2021.3071214

[53] Maya Siman-Tov, Irina Radomislensky, Kobi Peleg, H. Bahouth, A. Becker, I. Jeroukhimov, I. Karawani, B. Kessel, Y. Klein, G. Lin, O. Merin, M. Bala, Y. Mnouskin, A. Rivkind, G. Shaked, G. Sivak, D. Soffer, M. Stein, and M. Weiss. 2018. A look at electric bike casualties: Do they differ from the mechanical bicycle? *Journal of Transport & Health* 11 (2018), 176–182. https://doi.org/10.1016/j.jth.2018.10.013

[54] Mel Slater. 2003. A note on presence terminology. *Presence connect* 3, 3 (2003), 1–5.

[55] Mel Slater. 2018. Immersion and the illusion of presence in virtual reality. *British Journal of Psychology* 109, 3 (2018), 431–433. https://doi.org/10.1111/bjop.12305 arXiv:https://bpspsychub.onlinelibrary.wiley.com/doi/pdf/10.1111/bjop.12305

[56] 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

[57] Carlos Sun and Zhu Qing. 2018. Design and Construction of a Virtual Bicycle Simulator for Evaluating Sustainable Facilities Design. *Advances in Civil Engineering* 2018 (2018). https://doi.org/10.1155/2018/5735820

[58] 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)*. IEEE, Costa Mesa, CA, 19–26. https://doi.org/10.1109/3DUI.2012.6184179

[59] 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

[60] 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

[61] 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

[62] 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)*. IEEE, Costa Mesa, CA, 31–38. https://doi.org/10.1109/3DUI.2012.6184181

[63] Séamas Weech, Sophie Kenny, and Michael Barnett-Cowan. 2019. Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review. *Frontiers in Psychology* 10 (2019). https://doi.org/10.3389/fpsyg.2019.00158

[64] 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

[65] 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

[66] B. E. Westerhof, E. J. H. de Vries, R. Happee, and Arend Schwab. 2020. Evaluation of a Motorcycle Simulator. https://doi.org/10.6084/m9.figshare.11744328.v1

[67] Tetsuji Yamaguchi, Akira Yamada, Takeshi Fujiwara, Ryoichi Takahashi, Tetsuya Shimada, Yuki Ishida, Koichiro Ueda, and Shigeo Kaneda. 2018. Development of Bicycle Simulator with Tilt Angle Control Tilt Angle. *Proceedings - International Computer Software and Applications Conference* 2 (2018), 247–252. https://doi.org/10.1109/COMPSAC.2018.10238

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