What does it mean to cycle in Virtual Reality? Exploring Cycling Fidelity and Control of VR Bicycle Simulators

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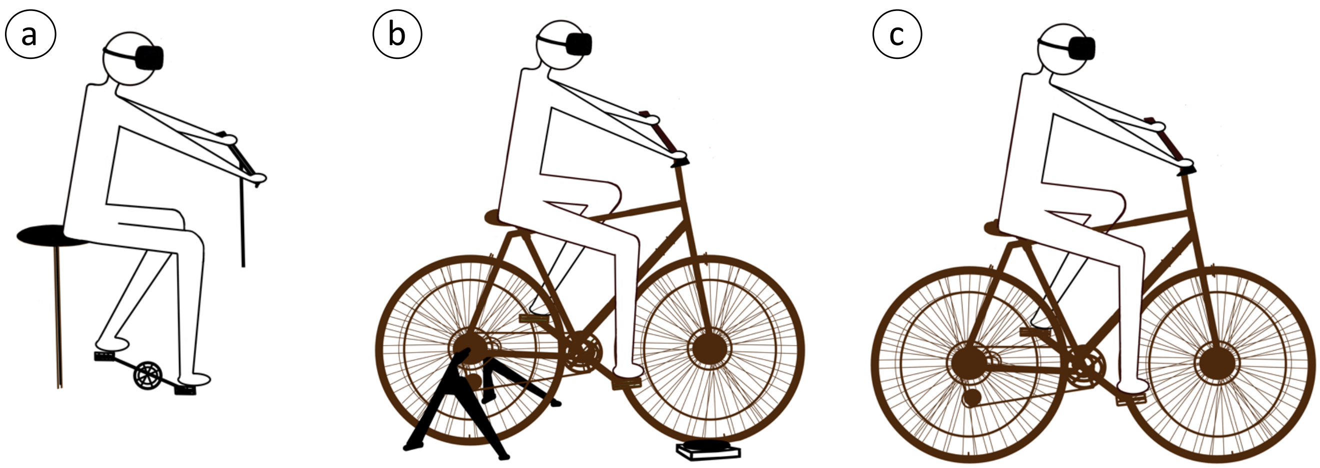

Figure 1: Overview of three levels of VR cycling fidelity: (a) cycling without a bicycle while sitting on a chair with a handlebar and pedals, (b) cycling on a stationary bicycle placed on the fixed platform, and (c) cycling on a dynamic bicycle moving through space.

ABSTRACT

Creating highly realistic Virtual Reality (VR) bicycle experiences can be time-consuming and expensive. Moreover, it is unclear what hardware parts are necessary to design a bicycle simulator and whether a bicycle is needed at all. In this paper, we investigated cycling fidelity and control of VR bicycle simulators. For this, we developed and evaluated three cycling simulators: (1) cycling without a bicycle (bikeless), (2) cycling on a fixed (stationary) and (3) moving bicycle (tandem) with four levels of control (no control, steering, pedaling, and steering + pedaling). To evaluate all combinations of fidelity and control, we conducted a controlled experiment (N = 24) in indoor and outdoor settings. We found that the bikeless setup provides the highest feeling of safety, while the tandem leads to the highest realism without increasing motion sickness. Moreover, we discovered that bicycles are not essential for cycling in VR.

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CCS CONCEPTS

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

KEYWORDS

virtual reality, cycling, locomotion, bicycle simulators

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1 INTRODUCTION

Bicycle simulators are an imitation of cycling for various applications, such as entertainment [1] [18], health [49], and research [29–31]. They play an essential role in maintaining cardiovascular health, improving physical shape through gamification [1, 18, 49], and provide a safe and low-cost evaluation platform for researchers [51]. Due to the advances in virtual reality (VR) technology and its advantages in enabling a high degree of presence and immersion in 3D environments, most of the existing bicycle simulators [4, 25, 27, 42, 51, 53, 61] are placed on stationary platforms

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

and use a VR headset to present a virtual world to users [13, 43]. However, one of the main limitations of such bicycle simulators is the lack of a whole cycling experience, including balance, coordination, and physical movement through space. Moreover, since the VR headset completely occupies the visual channel of cyclists, it is unclear what level of external realism and control over the bike is necessary to say that a person is riding a bicycle in virtual reality.

Creating highly realistic cycling experiences in VR can be time-consuming and expensive, and it is unclear whether it is always needed. Previous works have focused on bringing the virtual environment closer to reality by improving realism and immersion and reducing motion sickness. For example, Van Gisbergen et al. [52] have explored the effect of cycling realism in Virtual Reality on experience and behavior by comparing different levels of software fidelity, i.e., VR presentation of cycling simulation. Despite the differences in realism shown in the virtual world, they found no difference between low and high levels of software fidelity and their influence on experience and behavior. However, they underlined the importance of hardware fidelity, which has a more substantial effect on the cycling experience and requires careful consideration to facilitate a better experience and realism. As for the immersiveness and motion sickness, previous research has tried to address a mismatch between sensory and cognitive systems while cycling in VR by introducing motion platforms [57], external countermeasures to reduce motion sickness, and steering methods [34]. Based on this, Matviienko et al. [34] introduced two dimensions of addressing motion sickness for VR cycling: (1) design and (2) external countermeasures. While external countermeasures to reduce motion sickness in VR bicycle simulators have been systematically explored, the hardware fidelity of VR bicycle simulators and their effect on realism, safety, and motion sickness requires a deeper exploration, as suggested by Van Gisbergen et al. [52].

In this paper, we investigate levels of cycling hardware fidelity and control for Virtual Reality bicycle simulators (Figure 1). For this, we designed and evaluated three types of cycling setups: (1) cycling without a bicycle (bikeless), (2) cycling with a stationary bicycle (stationary), and (3) cycling on the moving bicycle (tandem) under four levels of cycling control (no control, steering, pedaling, and steering + pedaling). To evaluate cycling in VR on the moving bicycle, we proposed a tandem-based setup consisting of a tandem bicycle with steering and braking control on the back seat and a rider fully controlling the bicycle. In this simulator, a person sitting in the front in VR glasses can experience cycling with control over steering and pedaling in the virtual world. Moreover, this setup facilitates close-to-reality cycling conditions regarding acceleration forces and environmental factors. To evaluate all levels of cycling fidelity in VR, we conducted a controlled experiment (N = 24) in indoor and outdoor settings. The indoor part included cycling on the bikeless and stationary setups, and the outdoor covered cycling on the tandem. Our results showed that the bikeless cycling setup creates the highest feeling of cycling safety. In contrast, the tandem setup induces the highest level of cycling realism without increasing motion sickness. The control over both steering and pedaling leads to the highest level of cycling control over all three types of setups and, therefore, creates a higher level of cycling realism. Additionally, we discovered that bicycles are not essential in simulating cycling in virtual reality.

In summary, our research contribution includes:

- A systematic empirical evaluation of cycling hardware fidelity and control for Virtual Reality bicycle simulators to facilitate high realism and safety without increasing motion sickness.
- A tandem-based setup for bicycle simulators that enables a physical movement through space for cycling in Virtual Reality.

2 RELATED WORK

In this section, we provide an overview of existing developments of bicycle simulators through the prism of cycling realism, virtual reality sickness, and different levels of cycling fidelity and control.

2.1 Realism and Virtual Reality Sickness in Bicycle Simulators

Existing bicycle simulators are implemented at various levels of fidelity to reflect different levels of cycling realism and reduce virtual reality sickness. For this, researchers have utilized various software [46, 52] and hardware approaches [19, 45, 56, 60] to increase cycling realism, as well as visuo-vestibular modifications [12, 14, 16, 23, 28, 34, 40, 40, 50, 54, 55, 55] to reduce sensory conflicts and therefore virtual reality sickness in bicycle simulators. We outline these approaches in detail in the following.

2.1.1 Cycling Realism via Software and Hardware. The software approach to increase cycling realism involves modification of the simulation itself and the quality of the surrounding virtual environment. For example, Van Gisbergen et al. [52] have investigated the effect of cycling realism in Virtual Reality on cyclists' experience and behavior. They compared two simulations with low and high details about surrounding buildings and streets. They discovered that despite the differences in realism shown in the virtual world, i.e., software fidelity, they do not affect experience and behavior. Thus, even with a lower granularity of details about the virtual environment, cyclists had a high feeling of realism and presence. However, they mentioned that other variables, e.g., hardware fidelity, can affect the whole experience and facilitate a better sense of presence and realism. Since the hardware fidelity of bicycle simulators plays a more dominant role in the cycling experience, within the scope of this paper, we explore their hardware fidelity.

One of the main methods to increase cycling realism using hardware is to introduce an additional degree of movement of the stationary bicycle simulators, e.g., via motion platforms. For example, Herpers et al. [19] constructed a high-fidelity motion-based simulator, the FIVIS, which employs a hydraulic platform with six degrees of freedom. Another method to increase the degrees of freedom while cycling in bicycle simulators is via a tilting mechanism that physically moves the platform in response to the rider's weight shifts. For example, Yamaguchi et al. [60] added a tilt function by connecting the rear wheel to an industrial servomotor. Alternatively, this also can be enabled via passive movements, a motion platform [15], and a suspension system that follows the movements of cyclists. For instance, Shoman et al. [45] employed the idea of platform tilting but without additional information about how the tilt feature influences motion sickness and perceived realism. Lastly, researchers exploited alternate and scaled forces to facilitate a realistic perception in virtual reality [56]. However, these hardware modifications require additional complicated and often high-cost hardware, which limits the accessibility of such modifications to a wide population.

2.1.2 Virtual Reality Sickness. Virtual reality (VR) sickness [26], cybersickness [39], often Visually-Induced Motion Sickness (VIMS) [6] or simulator sickness [11] describes a range of symptoms such as nausea, headache, general malaise, and sweating that occur during and after being in a virtual environment. These terms are often used interchangeably, so in this paper, we refer to the above symptoms as virtual reality (VR) sickness. VR sickness is a common problem in VR environments caused by a sensory conflict that arises from the motion disparity between two sensory systems - visual and vestibular. This motivated researchers to explore ways to reduce VR sickness [9, 24, 41, 47] by employing two main approaches that focused on the (1) modification in the design of simulators and (2) adding external countermeasures [34].

External countermeasures typically include galvanic feedback [14, 28, 55], airflow [12, 16], bone-conducting vibration [54, 55], vibration on a seat [12], head [40, 40], and feet [23, 50] to enhance participants' sense of self-motion. Based on recent empirical investigations, it has been shown that airflow is effective in reducing motion sickness for cycling in VR simulators [34]. As for the design of simulators, recent works have shown that a handlebar steering [34] and platform tilt [57] induce the lowest level of motion sickness in Virtual Reality. However, the space of hardware design of VR bicycle simulators remains largely unexplored. Within the scope of this work, we explore how the fidelity of bicycle simulators from the hardware perspective, e.g., physical movement through space and absence of a bicycle, influence motion sickness and, therefore, cycling realism.

2.2 Cycling Control in Bicycle Simulators

Nearly all existing bicycle simulators include steering and pedalling [2, 5, 8, 17, 18, 20, 27, 36, 51, 53, 60] and some of them additionally contain brakes [17, 29, 35–38, 48]. Since steering and pedaling are essential for cycling in bicycle simulators [10, 44], we systematically explored these two types of controls, leaving braking out of scope for this paper. While pedaling requires measuring speed and transferring it to the simulation, steering was implemented in various ways, which we outline in detail in the following.

Researchers have facilitated steering in bicycle simulators using buttons by tilting the rider and rotating the handlebars (with or without a turntable). Katsigiannis et al. [21] explored steering with buttons on both sides of the handlebar. Upon pressing the button on the corresponding side, the bicycle would turn. However, this steering method lacks natural implicit interaction known from cycling on a bicycle in the real world. To create a more natural steering experience, researchers have explored steering methods based on the tilting of cyclists on platforms to reflect upper body movement as it is done on an actual bicycle. To facilitate the tilting of riders on bicycle simulators, researchers have employed cycling control methods based on moving platforms that reflect the physical movement of a cyclist on it. For example, a high-fidelity hydraulic platform [18] facilitates a close-to-reality simulation of turns and balance. The motion platform is fed by real forces and accelerations based on a mobile data acquisition system during real bicycle rides. This mimics the movements of the platform in the virtual environment and the rider's reaction. Yamaguchi et al. [60] presented a bicycle simulator with a tilt angle control for 3D virtual spaces. The tilt angle is based on the calculations of the control unit and an AC servomotor reflected by the movements of the cyclists' upper body. A less technically complex solution using a moving platform for cycling was systematically investigated by Wintersberger et al. [57]. They explored a motion-based bicycle simulator without centrifugal force simulation and discovered that weak tilting could significantly improve cycling realism without affecting cycling performance and increasing motion sickness. However, the main limitation of the setups with moving platforms to enable tilting and therefore steering via an upper body requires complicated and expensive setups with a high level of maintenance and low flexibility of changes. Moreover, Matviienko et al. [34] explored upper-body steering on a stationary bicycle simulator, and their results have shown an increased motion sickness with upper body steering compared to the handlebar method.

Handlebar rotation is often facilitated by the free movement of the handlebar with the front wheel on a floor [25, 42] or turntable [51]. Alternatively, it is implemented using a front wheel with a front-mounted fork and a movable handlebar [29–31]. In all these cases, the handlebar rotation in the horizontal plane is reflected in the simulator, i.e., rotating the handlebar 10° to the left rotates the camera view of the simulation by the same angle. Therefore, for all of our setups, we chose steering based on the handlebar rotation since it leads to the lowest motion sickness without losing the natural steering interaction.

3 CYCLING FIDELITY AND CONTROL

Designers and researchers face a trade-off between safety and realism when designing cycling environments. From one side, the cycling setup has to be safe without causing participants any harm, and from the other side, it has to mimic the cycling experience as close as possible to reality [33]. Typically, creating an indoor static bicycle simulator facilitates a high level of safety since participants are not exposed to external hazards, such as cars and other road users because they are presented as virtual objects in the simulation. However, such setups limit the cycling experience since cyclists do not have to balance and coordinate their movement and lack physical movement through space.

Virtual Reality (VR) technology allows us to explore the design space of bicycle simulators from a different angle and potentially find a solution that increases both safety and realism of the cycling experience. Moreover, control over a cycling process plays an important role in the influence of realism. Therefore, in our work, we focus on the hardware design of VR bicycle simulators and investigate which parts of the simulators play an essential role in the cycling experience in terms of movement through space and the extent the control plays in the cycling experience. For this, we explored two dimensions: (1) cycling (hardware) fidelity and (2) control over a bicycle.

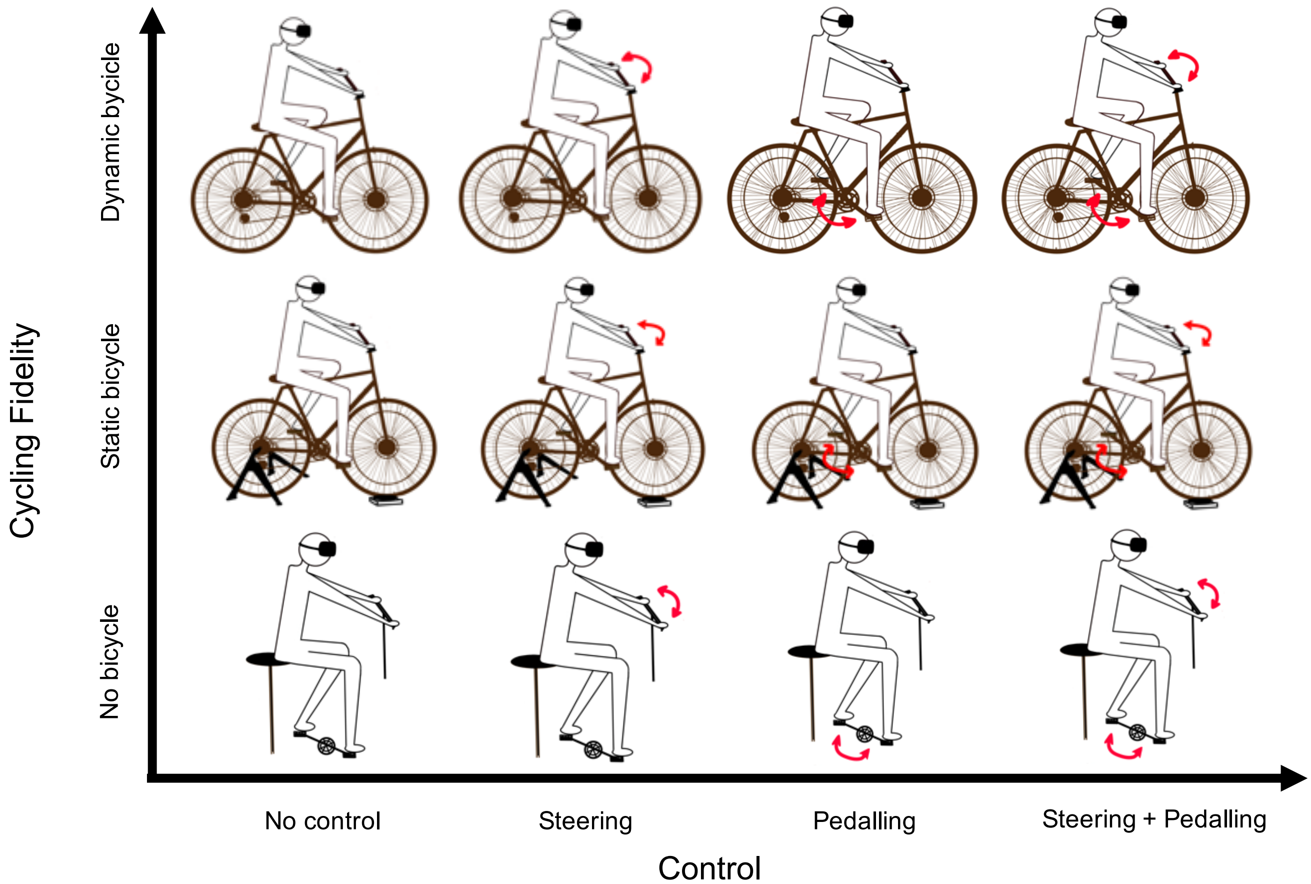

Figure 2: Overview of two dimensions: the Y-axis shows three levels of cycling fidelity, which include cycling without a bicycle, and cycling on a static and dynamic bicycle. The X-axis indicates four levels of cycling control, from no control over steering and pedaling to a combination of steering and pedaling.

3.1 Cycling Fidelity

We explore cycling fidelity in three stages: (1) no bicycle, (2) bicycle is fixed, and (3) bicycle is moving through space. The rationale behind cycling without a bicycle lies in the dominance of visual channels in virtual reality. Since steering and pedaling are two essential elements of cycling [10, 44], we mimic only them in the static environment under laboratory conditions. Thus, this setup consists of a handlebar, a pedaling trainer, a chair, and a VR headset. The aspect we aim to explore with this setup is whether a bicycle is needed for cycling in Virtual Reality and to what extent. This setup is based on the low-fidelity simulator presented by Woźniak et al. [59].

For the setup with a fixed bicycle, we increase the fidelity compared to the setup without a bicycle by adding a bicycle fixed on a platform and enabling steering and pedaling. We chose this setup based on most existing bicycle simulators in Virtual Reality [4, 25, 27, 42, 51, 53, 61] that include a bicycle fixed on a platform with steering and pedaling. The question we ask ourselves for this setup is what role an actual physical bicycle plays in the VR bicycle simulators since it is not visible to cyclists while cycling in VR.

3.1.1 Tandem-Based Setup for Cycling in Virtual Reality. For the cycling setup with a bicycle physically moving through space, we propose a tandem-based simulator that enables physical movement through space in Virtual Reality and requires the maintenance of balance and coordination. With this, we aim to increase the cycling fidelity one step further by adding a movement for the bicycle in VR while maintaining the consistency of control over steering and pedaling. This tandem-based simulator consists of (1) a tandem bicycle and (2) a cycling person sitting in the back seat of it (Figure 3c). The person sitting in the back of the tandem, i.e., an experimenter, has full control over the steering, braking, and pedaling. The person sitting in the front of the tandem, i.e., the participant, can have optional control over pedaling and rotating a handlebar in the same location since it is disconnected from the control of the actual tandem. The rotation of handlebar executed by a participant is reflected only in the VR simulation. With this, the tandem simulator further facilitates control over cycling, such as steering, pedaling, and no control, since they do not affect the cycling experience in the real world. To create a realistic cycling experience, the person cycling in the back of the tandem ensures smooth and safe cycling by pedaling evenly and avoiding additional noise and conversation. For safety reasons, when cycling outdoors, an experimenter can block pedaling of a participant by stopping pedaling and, therefore, avoid accidents with road users in the outside world. Via the presence of an additional person in control of a tandem, we aimed to ensure a safe cycling experience for a participant sitting in front of a tandem wearing VR glasses. The primary rationale behind our tandem-based simulator is to create a low-cost approach and bring a close-to-reality Virtual Reality cycling experience. We based this approach on the tandem-based simulator for self-driving bicycles [32].

By exploring these three levels of cycling hardware fidelity, we aim to investigate which setup reflects safe and realistic cycling gradually and, more importantly, which stage in this dimension reflects a realistic cycling experience in VR. Moreover, all three setups are minimal and low-cost and require a limited amount of hardware, such as a laptop, VR glasses, an Arduino board with a potentiometer, and (optionally) a bicycle. Within the scope of this paper, we excluded high-fidelity and high-cost cycling setups that require additional motion platforms and tracking systems.

3.2 Cycling Control

For the dimension of cycling control, we incrementally and systematically explore the following four stages: (1) no control, (2) steering, (3) pedaling, and (4) steering + pedaling. Since steering and pedaling are essential cycling elements [10, 44], we introduced them into cycling control step-by-step. With the option without control, we explore the idea of only holding the handlebar and feet placed on the pedals and the cyclist's position in relation to the handlebar and pedals. Their legs are placed on the pedals while sitting on a chair without any control over the cycling process. In this case, the cyclists are driven through a simulation at a constant speed of 20 km/h, and the steering is automated. This level of control, combined with the bikeless setup, reflects the baseline in which no bicycle and no control over it are given to participants. We deliberately excluded the situation without pedals and a handlebar that would imply sitting only on a chair to differentiate between cycling and other types of movement in VR, e.g., driving a car or riding a wheelchair. For the situations with only steering and pedaling, we investigate which activity plays a more dominant role in cycling. Therefore, we enable either steering or pedaling one at a time and explore when participants say they cycle. For pedaling, the steering was automated, and for steering, cyclists were driven at a constant speed of 20 km/h, as in the case with no control. Finally, for the last level of control, we enable steering and pedaling simultaneously to facilitate a higher level of control over cycling to investigate how it compares to the previous levels. By providing both steering and pedaling to cyclists, we aim to create a close-to-reality level of cycling control.

4 EVALUATION

To investigate the level of cycling fidelity and control in virtual reality, we conducted a controlled experiment in indoor and outdoor settings to investigate three levels of cycling fidelity and four levels of control over a bicycle. Therefore, for this experiment, we had the following research question: *How do cycling hardware fidelity and control influence cycling realism, feeling of safety, and motion sickness in Virtual Reality bicycle simulators?*

4.1 Participants

We recruited 24 participants (7 female, 17 male) aged between 18 and 35 years ($M = 24.79, SD = 3.72$) using social networks and personal contacts. Fourteen participants have previously experienced cycling in a stationary bicycle simulator and three – on a tandem. Seven participants cycle daily, seven – once a week, three – once a month, and seven at least once a year. Fourteen participants had little to no previous experience with VR. Participants did not receive any compensation for their participation.

4.2 Study design

The study was designed to be within-subject with two independent variables: *setup* and *control*. The cycling setup reflects cycling hardware fidelity and has three levels: (1) bikeless, (2) stationary bicycle, and (3) tandem simulation. We explored these three levels based on the idea of not having a bicycle at all (bikeless), having a bicycle on a stationary platform (stationary bicycle), and a bicycle moving through physical space (tandem). We utilized a handlebar, a foot trainer, and a chair for the bikeless setup. For the stationary bicycle, we placed a bicycle on a fixed platform. Finally, for the tandem, participants had to sit on a front seat of a tandem while physically moving through space, as described in the previous section. As for the level of control, we investigated four levels: (1) no control, (2) pedaling, (3) steering, and (4) steering + pedaling. Similarly to the gradual change for the types of simulators, for these four levels, we aimed to explore different levels of control, from not having it at all (= self-driving bicycle) through having one type of it (pedaling or steering) and full control (steering + pedaling). To explore all levels of independent variables, we created twelve experimental conditions by combining three setups and four levels of control. However, we wanted to avoid the situation in which participants had to switch between the same setups multiple times during the experiment to save time and facilitate convenience. Therefore, we used a Balanced Latin square twice. First, we counterbalanced the sequences of setups and then the control levels per each setup.

Both bikeless and stationary bicycle setups were investigated indoors under controlled lab conditions. The part of the experiment with a tandem simulator was conducted in the city park with occasionally passing cyclists and pedestrians without motorized vehicles for safety reasons. The park consists of a network of asphalt routes with multiple intersections. For all the experimental conditions with control, the participants' task was to cycle on a straight route of the same length (600 meters) in virtual reality and stay on the right side of the road while experiencing different levels of control. They were asked to control steering, pedaling, or steering and pedaling for the conditions that enabled these actions. Participants' task was to sit on a bicycle and follow the ride on a self-driving bicycle for conditions with no control. Each ride took around 2-3 minutes.

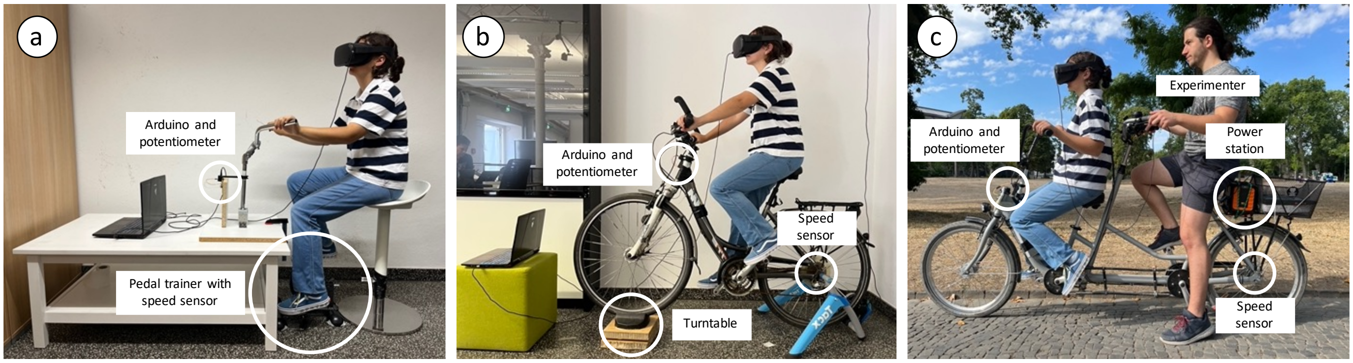

Figure 3: Overview of three cycling setups: (a) bikeless setup consists of a handlebar with an Arduino board and potentiometer mounted on the table, a pedal trainer with a speed sensor and VR glasses connected to a laptop, (b) bicycle simulator consists of a bicycle mounted on the stationary platform with a speed sensor and a turntable, an Arduino board with a potentiometer, and VR glasses connected to a laptop, (c) tandem consists of a tandem with a speed sensor, power station, an Arduino board with a potentiometer, and person in control of the tandem. The VR glasses are connected to the laptop placed in the basket at the back of the tandem.

4.3 Apparatus

4.3.1 Bikeless. This setup did not include a bicycle but consisted of two important bicycle components to facilitate steering and pedaling: (1) a handlebar and (2) a pedal trainer [2]. The handlebar (a stem diameter of 22.2 mm) was placed on an iron rod fixed on a wooden board, fixed to a table, to prevent the handlebar's movements forward or backward. The iron bar was thick enough to stabilise the handlebar and allow smooth steering. To measure the handlebar's rotation, we placed a potentiometer connected to an Arduino board on the same wooden board as the handlebar. Both the potentiometer and handlebar had a 3D-printed wheel connected with a toothed belt to transmit the rotation over a Wi-Fi connection. To measure the speed, we attached a Garmin speed sensor [3] to the pedal trainer, which transferred the speed value over ANT+ protocol directly to a laptop with a Unity project. This setup is shown in Figure 3a.

4.3.2 Stationary. The stationary setup represents the commonly used setup with a bicycle fixed on a platform. The back wheel of the bicycle (28 inches) was mounted on a *Tacx Satori Smart Trainer*[4] with a 1.6 kg flywheel, and the front one was placed in a turntable to facilitate rotation of the handlebar on the same position. Similarly to the bikeless setup, we added an Arduino board with a potentiometer to measure the rotations of the handlebar over 3D-printed wheels connected with a toothed belt and Garmin speed sensor to the rear wheel to measure the cycling speed. This setup is shown in Figure 3b.

4.3.3 Tandem. With the tandem setup, we facilitated the physical movement of a bicycle through space to create a higher feeling of cycling experience with balancing and coordination. We based this setup on the tandem approach for running experiments with cyclists proposed by Matviienko et al. [32], which has been shown to be safe and realistic for self-driving bicycles. To create a realistic and safe cycling VR experience, participants sat in the front seat of a two-wheeled Collettivo Tandem bicycle (24-inch, 226.82 x 101.6 x 51.82 cm, 26,5 kg). They were driven outdoors in the city park by a person sitting in the back. For the experimental conditions with steering, we loosened the front handlebar to enable its free rotation without actually steering a bicycle. The actual control over the steering of the tandem was given to the experimenter. Similarly to the bikeless and stationary setups, we added two Arduino NodeMCU boards with a potentiometer to both handlebars to measure the rotation angle and transfer it directly to the laptop with a Unity project placed in the rear basket of the tandem. The same Garmin speed sensor was attached to the center of the rear wheel to measure the cycling speed and was transferred to the laptop using ANT+ protocol. For the power supply, we used XTORM Xtreme Power Power Station 78000 mAh [5] to provide a power supply for the laptop, and two power banks for both Arduino boards. This setup is shown in Figure 3c.

Participants' steering and pedaling actions are directly reflected in the VR simulation for all three setups. If the pedals are not turned, a bicycle automatically slows down to a stopping position for the bikeless and stationary setups and via brake activation by an experimenter for the tandem setup. For all setups, the steering enables complete maneuvering control over a bicycle, including a U-Turn. Moreover, we employed the same steering method via rotation of a handlebar for all three setups as a steering method because it induces the lowest level of motion sickness, and has higher usability, accuracy, and realism compared to the steering with an upper body, i.e., weight shifting [34].

4.3.4 VR software and hardware. For all three setups, we used the same gaming laptop with 16 GB of RAM, a *Nvidia GeForce GTX*

[2] *Himaly Mini Bike Hometrainer:* https://www.amazon.de/gp/product/B091GGFP39/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
[3] https://www.garmin.com/de-DE/p/641221
[4] https://www.garmin.com/en-US/p/690891
[5] https://www.xtorm.de/products/power-station-portable-300-watts-78000-mah-xtreme-power-black-orange-upgrade

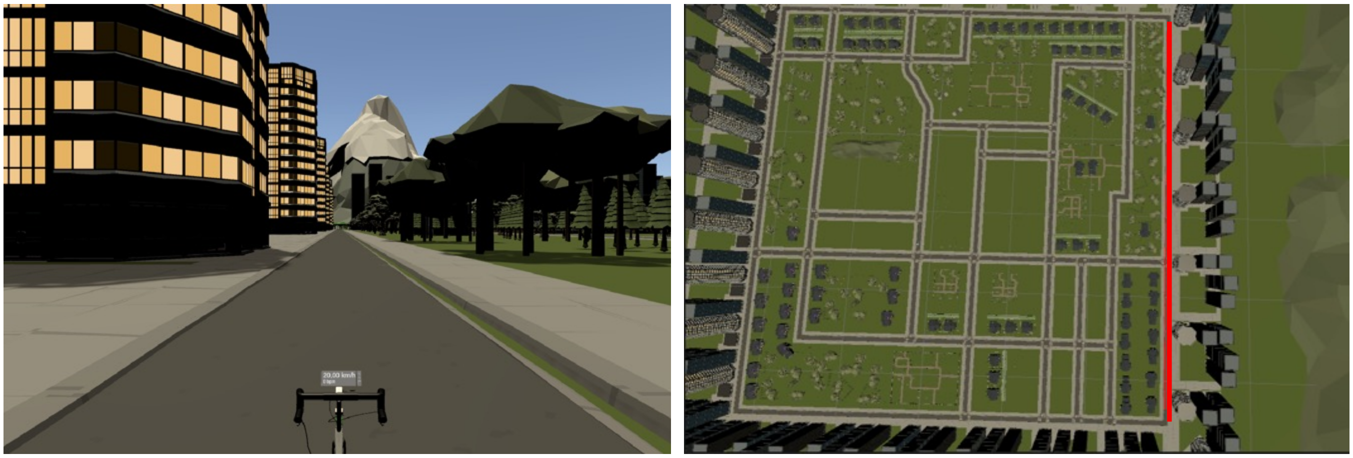

Figure 4: In the experiment, participants had to cycle on a straight route (marked red on the right) with buildings and trees placed on the sides of the road. The first-person perspective is shown on the left, and the bird's eye view – on the right).

1060[6] graphics card and an *Intel Core i7-7700HQ*[7] processor with a base frequency of 2.80 GHz. To present the VR environment to the participants, we employed an *Oculus Quest 1*[8] Virtual reality glasses as the Head-mounted display (HMD). The glasses have six degrees of freedom and track the head and body movement with high precision in the virtual environment without additional external sensors. The HMD has a resolution of 1440 x 1600 pixels for each eye and a refresh rate of 72 Hz. To implement the virtual environment, we used the Unity game engine [9] version 2020.1.12f1. For rendering the virtual scene into the HMD, we used the SteamVR plugin[10] from the Unity assets store.

The virtual environment was consistent for all experimental conditions and consisted of a straight route with buildings and trees placed on the sides of the road (Figure 4). We focused exclusively on cycling on a straight route due to the technical difficulties of matching turns from the real world to a virtual world for the tandem setup. This matching between real and virtual turns requires a precise technical setup to facilitate turns and to avoid situations in which a cyclist turns a handlebar in the real world before or after it happens in a virtual world and vice versa. Since we did not want to affect cyclists' perception and cycling experience due to this technical challenge, we conducted the experiment on a straight route, leaving cycling with a tandem setup with turns for future work.

4.4 Measurements

To investigate the level of the cycling realism for different levels of cycling fidelity and control, we measured the following dependent variables:

- *Virtual Reality Sickness*: for each (out of three) setup, participants filled in the questions from the Simulation Sickness Questionnaire (SSQ) to assess their general state of motion sickness after cycling. To calculate the SSQ score [22], we used the formula from [3]. Total SSQ scores of 20-30 reflects minimal to moderate motion sickness and greater than 40 suggest "a bad simulator" [7].
- *Presence*: after each setup, every participant assessed the feeling of presence in the virtual environment using the Igroup Presence Questionnaire (IPQ). The IPQ questionnaire consists of all subscales range between 1 (lowest) and 7 (highest): general presence, spatial presence, involvement, and experienced realism. The scores were calculated based on the official source for the IPQ questionnaire [11].
- *Cycling performance*: for all conditions, we logged speed, steering angles, and head rotations of cyclists to assess changes in cycling behavior over different levels of fidelity and control.
- *Subjective level of motion sickness, realism, and safety*: for every condition, we asked participants to assess their level of motion sickness and realism of the tested setup, as well as how safe they found it using a 5-point scale (1 – strongly disagree or low motion sickness/realism/safety, 5 – strongly agree or high motion sickness/realism/safety) for the following statements: (1) "I feel motion sickness after this cycling experience", (2) "I found this cycling experience realistic", and (3) "I found this cycling experience safe".
- *Ranking:* for each setup, participants had to rank the levels of control in terms of motion sickness, realism and safety. At the end of the study, participants were asked to rank each setup in terms of motion sickness, realism, and safety.

4.5 Procedure

After obtaining informed consent, we collected participants' demographic data. Afterwards, we provided a brief overview of the procedures, which included explanations of the types of setups and levels of control. Participants familiarized themselves with

[6]https://www.nvidia.com/de-de/geforce/graphics-cards/gtx-1660-ti/
[7]https://ark.intel.com/content/www/us/en/ark/products/97185/intel-core-i77700hq-processor-6m-cache-up-to-3-80-ghz.html
[8]https://www.oculus.com/quest/refurbished/
[9]https://unity.com/
[10]https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647
[11]http://www.igroup.org/pq/ipq/data.php

	SSQ								IPQ			
	Total		Nausea		Oculomotor		Disorientation		GP	SP	INV	ER
	M	SD	M	SD	M	SD	M	SD				
Bikeless	29.0	35.9	26.2	41.5	17.1	20.0	38.3	47.4	5.0	2.8	3.7	2.1
Stationary	32.0	39.8	24.6	36.0	18.3	25.4	49.8	58.6	5.0	3.0	3.8	2.5
Tandem	23.5	26.9	20.7	27.7	13.6	15.0	32.5	45.5	5.5	3.0	4.1	2.3

Table 1: Summary of results per cycling setup: the table shows mean and standard deviation values for SSQ scores and its sub-scores and Igroup Presence Questionnaire score (IPQ) as medians per subscale. GP = General Presence, SP = Spatial Presence, INV = Involvement, ER = Experienced Realism. Total SSQ scores of 20-30 reflects minimal to moderate motion sickness and greater than 40 suggest "a bad simulator" [7] and IPQ scores for all subscales range between 1 (lowest) and 7 (highest).

the bikeless setup, stationary bicycle, and tandem bicycle during a test ride. Once the participants felt comfortable, we started experimental conditions. During the experiment, participants had to cycle on a straight route with different levels of control. Their task was to maintain (when applicable) the bicycle within a road and safely finish the ride. After each ride, participants received several questions about the realism, safety, and motion sickness they experienced during a ride. At the end of the study, we interviewed the participants about their preferences for cycling simulators and control levels. The cycling part of the study took about one hour, and the entire study lasted approximately one and a half hours. The study was conducted with approval from the ethical review board at our university. During the recruitment process, we asked participants if they were prone to motion sickness and instructed them about the risk of getting it during the experiment. None of them reported any problems with motion sickness from previous VR experiences. For the tandem setup, participants were instructed to hold on to the handlebar and eliminate unnecessary side-to-side movements for all experimental conditions to avoid falling in case of disorientation and mental disconnect from the real world. The experimenter was instructed to activate brakes when participants leaned too much left or right, verbally notify them of slowing down in case of external changes, e.g., a pedestrian, and use emergency braking in potentially dangerous situations. As a result, these safety measures led to no incidents during the experiment.

5 RESULTS

We found that the bikeless cycling setup creates the highest feeling of cycling safety and the tandem setup induces a high level of cycling realism without increasing the motion sickness. Moreover, the control over steering and pedaling leads to the highest level of cycling control over all three types of setups. Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [58]. Therefore, we applied an Aligned Rank Transform (ART) ANOVA for all statistical analyses presented below. For pairwise comparisons, we used a Bonferroni correction. We outline all results in detail in the following subsections.

5.1 Virtual Reality Sickness and Presence

We found that three investigated cycling setups (bikeless, stationary , and tandem) induce a comparably low level of motion sickness based on the SSQ scores. This was shown by non-significant effects on the overall SSQ score and the sub-score of nausea, disorientation, and oculomotor ($p > 0.05$). However, we observed a tendency for lower SSQ scores for the tandem setup compared to the bikeless and stationary setups. Particularly, cycling on a tandem had the lowest total SSQ score ($M = 23.5, SD = 26.9$), followed by bikeless ($M = 29, SD = 35.9$) and stationary ($M = 32, SD = 39.8$) setups. Similar tendencies were also observed for the sub-scores of SSQ. For the nausea, the tandem setup had the lowest score ($M = 20.7, SD = 27.7$), followed by the stationary ($M = 24.6, SD = 36$) and bikeless ($M = 26.2, SD = 41.5$) setups. For the oculomotor, the tandem setup had also the lowest score ($M = 13.6, SD = 15$), followed by the bikeless ($M = 17.1, SD = 20$) and stationary ($M = 18.3, SD = 25.4$) setups. Finally, for the disorientation sub-score, we found that the tandem setup had the lowest score ($M = 32.5, SD = 45.5$), followed by the bikeless ($M = 38.3, SD = 47.4$) and stationary ($M = 49.8, SD = 58.6$) setups. The summary of the SSQ scores is shown in Table 1 and Figure 5.

We calculated the IPQ scores for the general presence and its subscales, which are shown in Table 1. Our analysis has shown that our cycling setups induced a comparable level of presence in the virtual environments, given no statistically significant differences ($p > 0.05$) for the general presence and all subscales. However, similar to the SSQ scores, we observed a tendency for a higher level of presence with the tandem setup compared to the bikeless and stationary ones.

5.2 Cycling Performance

5.2.1 Speed. We discovered that our participants cycled at a comparable speed (around 20 km/h) for both bikeless and stationary setups. For the tandem setup, the cycling speed was lower for all types of control: no control – 17.6 km/h, steering – 13.1 km/h, pedaling – 18.4, and steering + pedaling – 15.5 km/h. This finding was supported by statistically significant main effects for both setups ($F(2, 37) = 159, p < 0.001, \eta^2 = 0.9$) and controls ($F(3, 63) = 26.5, p < 0.001, \eta^2 = 0.56$). The post-hoc analysis for the setups has shown that participants were cycling slower on the tandem compared to the bikeless ($p = 0.013$) and stationary setups ($p < 0.01$). However, we did not observe statistically significant differences between the bikeless and stationary setups regarding cycling speed ($p > 0.05$). As for the post-hoc analysis for the controls, we found that cycling with no control was faster than with steering ($p < 0.01$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$). Additionally, we observed a statistically significant interaction effect for setups * controls

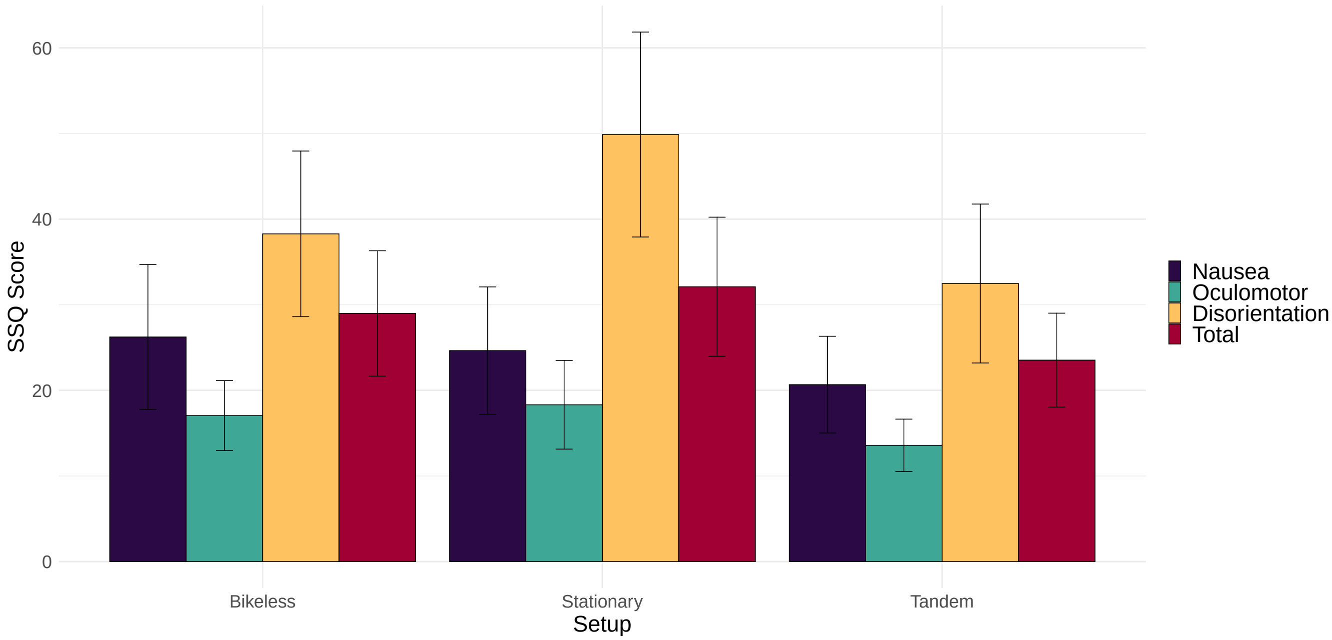

Figure 5: Overview of the total SSQ scores and its sub-scores (nausea, oculomotor, disorientation) with means and standard errors for the types of cycling setups.Total SSQ scores of 20-30 reflects minimal to moderate motion sickness and greater than 40 suggest "a bad simulator" [7].

($F(6,137) = 12, p < 0.001, \eta^2 = 0.34$), which indicates that participants were cycling faster with various types of control with the bikeless and stationary setups compared to the tandem ($p < 0.05$). Due to the lack of space, we are not reporting all pairwise comparisons from the interaction effect.

5.2.2 Steering. Based on the logging data, we found that participants rotated the handlebar more actively using the tandem setup for all types of control compared to the bikeless and stationary setups. This findings was confirmed by two statistically significant main effects for both setups ($F(2,37) = 8.7, p < 0.001, \eta^2 = 0.32$) and controls ($F(3,63) = 9.4, p < 0.001, \eta^2 = 0.3$). However, due to the p-value correction, none of the pairwise comparisons for the setups were statistically significant. The post-hoc analysis for the controls has shown that participants were more active in using the handlebar while steering compared to the situations with no control ($p < 0.01$). Lastly, we observed a statistically significant interaction effect for setups * controls ($F(6,137) = 9.7, p < 0.001, \eta^2 = 0.3$), which indicates that participants were more active in using the handlebar for the stationary setup while steering and pedaling than in the situation with no control ($p < 0.001$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$).

5.2.3 Head movements. Lastly, from the analysis of head movements along the Y-axis, i.e., turns left and right, we discovered that participants were more actively turning their heads left and right while cycling on the tandem than in the bikeless and stationary setups. This finding was confirmed by two statistically significant main effects for both setups ($F(2,37) = 66, p < 0.001, \eta^2 = 0.78$) and controls ($F(3,63) = 938, p < 0.001, \eta^2 = 0.98$). The post-hoc analysis for the setups has shown that participants were more actively turning their heads left and right while cycling with the tandem compared to the bikeless ($p < 0.001$) and stationary ($p < 0.01$) setups. The post-hoc analysis for the controls has shown that cyclists were more actively turning their head left and right while steering and pedaling rather than cycling with no control ($p < 0.001$), as well as more with steering and pedaling than only pedaling ($p < 0.001$) or steering ($p < 0.001$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$). Finally, we did not observe a statistically significant interaction effect for setups * controls ($F(6,137) = 1.1, p > 0.05, \eta^2 = 0.05$).

5.3 Likert Scale Results: VR Sickness, Realism, Safety

In the following, we outline the statistical analysis of subjective feedback based on the Likert scale. The summary of the descriptive statistics is shown in Table 2 and Figure 6.

5.3.1 VR Sickness. We found that participants had a comparable level of motion sickness reported from the Likert scale questions after each condition for all three setups and four levels of control. This finding was supported by a non-statistically significant main effect for both setups ($F(2,45) = 0.25, p > 0.05, \eta^2 = 0.01$) and controls ($F(3,67) = 2.54, p > 0.05, \eta^2 = 0.1$).

5.3.2 Realism. As for the realism of the cycling experience, we discovered that cycling in VR with more control. i.e., both steering, pedaling, and movement on a bicycle through space lead to a higher

		Speed		Steer.	HR	Motion Sickness			Realism			Safety		
Setup	Control	M	SD	SD	SD	Md	IQR	Rank.	Md	IQR	Rank.	Md	IQR	Rank.
Bikeless	Nothing	20.0	0	3	31	1.5	1.25	15	2	1	1	5	0	20
	Steering	20.0	0	8	17	1	1	1	3	1.25	2	5	0	1
	Pedaling	20.2	5	4	14	1	2	2	3	1.25	2	5	0	0
	Steer. + Ped.	20.7	5	6	12	1.5	1	6	4	1	19	5	0.25	3
Station.	Nothing	20.0	0	9	22	1	1	14	2.5	1	1	5	0	20
	Steering	20.0	0	10	47	2	1.25	3	3	2	1	5	0	1
	Pedaling	25.5	6	28	15	1	1	1	3	1	3	5	1	0
	Steer. + Ped.	22.4	6	6	9	2	1	6	4	2	19	4.5	2	3
Tandem	Nothing	17.6	3	34	9	1	0.25	15	3	2.25	3	4	2	18
	Steering	13.1	7	12	26	1	1	1	3	1	3	4	2	1
	Pedaling	18.4	4	25	9	1	1	2	3	2	7	4	1.25	5
	Steer. + Ped.	15.5	6	16	29	2	2	6	4	2.5	11	3	2	0

Table 2: An overview of results for the objective measures (speed, steering deviation, and head rotations), the subjective feedback using 5-point Likert scales, and ranking responses pro setup and type of control. 1 – low motion sickness/realism/safety, 5 – high motion sickness/realism/safety. Station. = Stationary, Steer. = Steering, Ped. = Pedaling, HR = Head Rotation, M = Mean, SD = Standard Deviation, Md = median, IQR = interquartile range, Rank. = Ranking.

realism of cycling. These findings were supported by statistically significant main effects for both setups ($F(2, 45) = 4.6, p = 0.015, \eta^2 = 0.17$) and controls ($F(3, 67) = 10.36, p < 0.001, \eta^2 = 0.32$). The post-hoc analysis for the setups has shown that tandem was perceived statistically more realistic than the bikeless setup ($p = 0.011$). The post-hoc analysis for the controls has shown that steering + pedaling was perceived statistically more realistic than steering ($p < 0.01$) and no control at all ($p < 0.001$). Moreover, pedaling was perceived statistically more realistic than no control at all ($p < 0.01$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$). Lastly, we observed a statistically significant interaction effect for setups * controls ($F(6, 137) = 3.9, p < 0.01, \eta^2 = 0.15$). However, due to the p-value correction, none of the pairwise comparisons were statistically significant.

5.3.3 Safety. As for the feeling of safety, we found that the tandem setup and full control over cycling lead to a lower level of safety. These findings were confirmed by two statistically significant main effects for both setups ($F(2, 45) = 37.5, p < 0.001, \eta^2 = 0.62$) and controls ($F(3, 67) = 20.6, p < 0.001, \eta^2 = 0.48$). The post-hoc analysis for the setups has shown that the bikeless setup was perceived statistically significantly safer than stationary ($p < 0.001$) and tandem ($p < 0.001$) setups. Moreover, the stationary setup was perceived statistically significantly safer than the tandem ($p < 0.01$). The post-hoc analysis for the controls has shown that no control at all was perceived statistically significantly safer than pedaling ($p < 0.001$), steering ($p < 0.001$), and both steering and pedaling ($p < 0.001$). Additionally, we observed that pedaling was perceived safer than steering and pedaling combined ($p < 0.01$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$). Lastly, we observed a statistically significant interaction effect for setups * controls ($F(6, 137) = 9.3, p < 0.001, \eta^2 = 0.29$). The post-hoc analysis has shown that cycling on bikeless setup with no control is perceived safer than the stationary bicycle with steering ($p < 0.001$) and the bikeless setup with both steering and pedaling ($p < 0.001$). Additionally, we discovered that cycling on a bikeless setup with pedaling is perceived as less safe than steering and pedaling ($p < 0.001$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$).

5.4 Ranking of setups and controls

We discovered that the majority of the participants found the tandem setup the most realistic (N = 14), followed by the stationary (N = 9) and bikeless (N = 1) setups. As for the question, which setup induces the lowest level of motion sickness, participants split almost in half between the bikeless setup (N = 10) and the tandem (N =9), followed by the stationary setup (N = 5). As for the ranking of safety, the majority of participants mentioned that they found the bikeless (N = 15) setup to be the safest, followed by the stationary (N = 7) and tandem (N = 2) setups. As for the rankings of controls, for all three setups we discovered that participants perceived having no control over a bicycle as the one that induces the lowest level of motion sickness (bikeless - N = 15, stationary - N = 14, and tandem - N = 15) and feels safer (bikeless - N = 20, stationary - N = 20, and tandem - N = 18). With the full control over bicycle (steering + pedaling) participants felt all three setups more realistic (bikeless - N = 19, stationary - N = 19, and tandem - N = 11). The summary of the rankings is shown in Table 2.

5.5 Problems and Preferences

Based on the qualitative feedback from the participants, we discovered that there were marginal differences between the bikeless and stationary setups in terms of realism, given that both setups felt robust and created a high feeling of safety and control. As for the tandem setup, cyclists found it very realistic due to the physical movement through space, experienced a high learning curve, and a high feeling of safety due to the presence of another person in control. We outline these findings in detail in the following.

5.5.1 Bikeless vs. Stationary vs. Tandem. The participants found the bikeless setup stable and therefore felt safer. For example, they noted that: *"The more fixed the setup, the more it felt safe."* [P4]

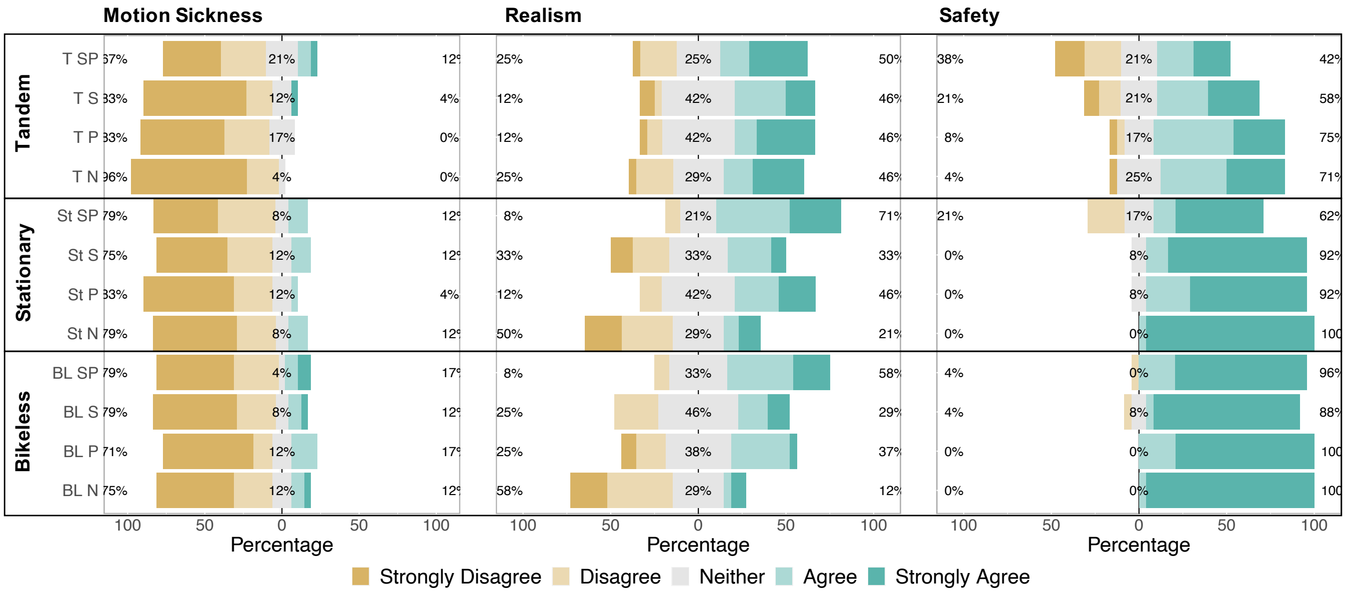

Figure 6: An overview of Likert data for each question split by a type of setup and control: motion sickness, Realism, and Safety. Strongly disagree indicates low motion sickness/realism/safety and strongly agree represents high motion sickness/realism/safety. T = Tandem, St = Stationary, BL = Bikeless, SP = Steering + Pedaling, S = Steering, P = Pedaling, N = Nothing.

and *"Nothing can happen when using the bikeless setup."* [P8]. When comparing the stationary and bikeless setups, participants said that *"the stationary bike felt almost as safe as the bikeless setup except it felt a little more wobbly."* [P16]. Moreover, P17 mentioned that *"you know that you can't go anywhere rather than that place"*, which refers to no problems with the perception of safety. However, some participants felt the lack of cycling realism and physical movement. For instance, some of them mentioned: *" I felt like it's not real and I will not fall."* [P15] and *"The bikeless setup is fixed regarding any movement."* [P9]. Participants liked the stationary setup for the reasons similar to the bikeless setup, such as the robustness of the setup, a good feeling of control, and higher feeling of safety. Some participants mentioned: *"The stationary setup felt more robust."* [P3], *"I felt like I had the most control with the stationary bike."* [P23], and *"The stationary and bikeless are similar to each other for safety; I don't know which is safer."* [P24]. The tandem setup was perceived as the most realistic due to the physical movement in the real world and as safe because one person controls the tandem. Our participants reported that: *"The tandem setting is a bit stressing at the beginning but feels better the more you experience it."* [P8], *"For the reason to have a backup person who controls everything in the background, I felt the safest on the tandem, even though it was in an area with traffic."* [P14], and *"Movement made it more realistic."* [P7]. On the contrary, there is still space for improvement of the tandem setup. Participants noted a lower level of environmental awareness and a lack of control compared to the bikeless and stationary setups. For instance, P2 said that *"On the tandem, you feel the wind that is in the real world, and it's harder for you to understand what's happening."*. P23 also mentioned that *"During the tandem scenario, you had to rely on someone else."*.

5.5.2 Controls and Setups. The control over a bicycle played a prominent role in increasing cycling experience in virtual reality. The ability of steering and pedaling made it feel more like cycling compared to no control at all, which felt like a tour around town on a self-driving bicycle. The qualitative feedback from participants supports these findings: *"Pedaling and steering always felt most realistic."* [P3], *"The phases without control felt like a tour around the town and not real immersive. So some level of control is necessary but you should feel as if you can manage it."* [P4]. Additionally, participants commented on the lack of steering experience for the bikeless and stationary setups. For example, they noted that it would be more realistic to have *"leaning on the bikeless setup"* [P18], because it creates a higher realism, given that *"I hardly ever steer using the handlebar. Rather I usually tilt my bike."*[P23]. As for the setups, participants mentioned the importance of communication while cycling with a tandem setup and add cycling noise to increase realism. For example, P1 noted that *"During the tandem usage it's important to communicate a lot, e.g., which direction you have to move your head to."*. P15 added that it would help to augment cycling setups with *"a noise to make it more realistic"*. As for the general comments, the cyclists noted that *"adding a fan for the bikeless and stationary setups would increase realism"* [P23]. However, *the overall experience was quite fun and educational, as someone who had never tried any type of VR experiment like this before that involved a lot of locomotion in the real world."* [P16].

6 DISCUSSION AND FUTURE WORK

In general, our results indicate that cycling realism, feeling of safety, and motion sickness in VR bicycle simulators can be addressed by

(1) hardware (setup) fidelity and (2) cycling control. As shown by the results from our experiment, the former has demonstrated that a bicycle is not an essential element of cycling in VR, and cycling without a bicycle leads to the highest feeling of safety. Even though the proposed tandem-based cycling method in virtual reality induces the highest level of cycling realism, it requires further design considerations in control, e.g., augmentation of braking. While it is crucial for cyclists to fully control a bicycle in VR for a realistic experience, our results have further demonstrated that both steering and pedaling are essential for all levels of hardware fidelity of bicycle simulators.

6.1 No need for a bicycle to cycle in VR?

Given the dominance of a visual channel in Virtual Reality, our results indicated that cycling in VR does not require an actual physical bicycle, which applies to cycling on a bikeless setup. While cycling with only a handlebar and pedaling trainer, our participants reported the setup's robustness and a feeling of cycling. The fixed setup created a high feeling of cycling safety because cyclists were not afraid to fall or hurt themselves. Additionally, participants reported a comparable feeling of safety in both the bikeless and stationary setups. However, as expected, they lacked cycling realism in indoor settings. In contrast, our proposed tandem-based setup induced the highest level of realism due to the physical movement through space and additional environmental conditions, such as ambient sounds and wind. However, the tandem-based setup poses the challenge of making the setup safer and more trustworthy. This can be further achieved via longer test rides before experiments or recruitment of trustworthy and experienced cyclists to control the tandem. However, we have demonstrated that our proposed tandem-based simulator pushes the boundary of experiencing cycling in VR with a higher level of realism compared to existing indoor setups, which according to our knowledge, have not been explored before.

As can be seen, on the one hand, participants felt safer because there was no movement through space when the setup was fixed and bikeless, but on the other hand, they lacked realism introduced by a tandem. These findings lead us to conclude that a two-wheeled bicycle is not necessary to simulate cycling in VR since participants perceived a bikeless setup as safe *cycling*, and the movement through space on the tandem increases the simulation realism. However, it is essential to introduce an appropriate level of control, i.e., at least with steering and pedaling, and movement through space, e.g., via a tandem-based simulator, as has been shown from the results of our study. The tandem-based simulator remains an exception because the more control cyclists have over a tandem simulator, the less safe they feel. This requires careful consideration of how cycling controls should be integrated and implemented into a tandem simulator to improve a feeling of safety without decreasing realism. Another work about a tandem simulation to mimic a self-driving bicycle reported a high safety level for simulation [32], given the presence of another person in control and trust towards this person. This confirms that the feeling of safety increases with more control given to a person controlling the tandem. Thus, the more control is given to a person controlling the tandem, the less responsibility the cyclists feel, leading to a higher safety level. Therefore, future research faces two main challenges regarding the safety-realism trade-off: (1) how to introduce movement to fixed indoor setups to increase realism and (2) how to create a feeling of safety on the tandem-based setup and maintain a high level of realism.

6.2 Cycling in VR is about Control

Cycling in VR is about controlling a bicycle rather than having a physical bicycle. Our results indicate that most people prefer full control over cycling in VR regardless of cycling fidelity. This finding also indicates higher importance of control than the hardware fidelity of the setups. In other words, a more realistic and safer cycling experience in VR is achieved via complete control over a cycling process rather than having an actual two-wheel bicycle as a part of the simulator. As further shown by our results, all three cycling setups induce comparable motion sickness and a feeling of presence in the cycling simulation. This confirms the previous findings that the steering method based on the handlebar in the VR bicycle simulators maintains a low level of motion sickness [34]. Moreover, given that the simulation was the same over all types of setups, we confirmed findings by Van Gisbergen et al. [52] regarding a little influence of the software fidelity on the cycling experience due to a comparable level of presence.

The measures from the cycling behavior indicate that cyclists were more active in turning their heads and steering while cycling on the tandem-based simulator but were cycling slower. There can be two possible reasons to explain this finding. The first one is the novelty of the cycling setup compared to the bikeless and stationary ones, which most participants had previously experienced. The second one is possibly related to a higher realism of the experience and, therefore, a more careful behavior reflected via a lower speed and higher frequency of head and handlebar rotations. Increased head and handlebar rotation frequency can also indicate cyclists' willingness to balance on a tandem and create more stable coordination of movements via controls since control over a tandem in the real world was not up to them. All-in-all, we can observe that cycling is a lot about control that substantially influences the cycling experience, including its realism and feeling of safety.

Although participants only experienced cycling on straight routes, we can already observe a big influence of control on the cycling experience following the idea: "the more control, the better". However, future work will have to investigate the influence of more complicated trajectories, including left and right turns and cycling up- and downhill. We assume that the necessity for control over a bicycle will increase not only through steering and pedaling but also in the movements of the upper body and braking activities. Within the scope of this paper, we did not explore more complex scenarios due to the technical limitations and difficulties with matching physical and virtual turns. For example, it is essential to turn at the right position in the real world without delays in the virtual world to create a realistic simulation. An exact cm-level position of the bicycle is necessary to create a seamless experience for cycling with turns using the tandem simulator. This poses a further technical challenge for future work.

6.3 Practical implications

Different levels of cycling fidelity in VR can be used depending on the goal of the experiments. Cycling on a bikeless setup can be used for situations requiring the high confidence of cyclists or risk-taking scenarios. For situations that require a higher level of realism, future experimenters can employ a tandem-based setup that requires balancing and coordination. Thus, regardless of bicycle fidelity, they all must facilitate full control over steering and pedaling.

With a growing demand for virtual reality entertainment, the experience of cycling in a home environment might require a lesser amount of additional hardware, e.g., a handlebar, a pedal trainer, and VR glasses. This can turn cycling into a more attractive, space-saving, and low-cost activity for both gaming and training. Moreover, depending on the level of control, not only cycling can be simulated in VR using a tandem-based simulator at a low cost, but also E-Scooter riding and other modes of micro-mobility, including self-driving experience in the full absence of control. For instance, E-Scooter riding can be achieved by providing only the steering, and no control to replicate the self-driving cycling experience.

7 LIMITATIONS

The proposed dimension of control can be further extended with braking and other intermediary steps, and future work can explore how the control over braking additionally influences cycling realism. Our work created a starting point for exploring different levels of fidelity and control for VR cycling. Since the tandem part of the experiment was conducted in the city park with other pedestrians and cyclists, it could have affected the participants' perception of safety. Future setups might need to include ambient sounds and airflow into the stationary setups in the laboratory environments, or the tandem setup should be employed in the empty restricted area without additional auditory distractions. However, the tandem-based VR simulator was close to reality and included environmental sounds and background noise, potentially increasing the proposed setup's ecological validity. The steering experience in our experiment was not based on leaning and weight distribution common for cycling in the real world. Instead, we employed the steering method via a handlebar rotation for all three setups that induces low motion sickness and leads to higher usability, accuracy, and cycling realism [34]. Exploring different steering methods, e.g., based on weight shifting, across the setups with varying hardware fidelity and not only a stationary setup poses an interesting question for future research. We acknowledge that VR sickness increases with age and time spent in VR simulation. Therefore, our experiment focused mainly on younger participants (between 18 and 35 years of age), and the experiment duration was less than two hours. Therefore, future studies need to be conducted with other age groups and different duration of cycling. Lastly, we only explored cycling in a straight line due to the technical limitations and difficulties mapping physical turns to virtual ones. Thus, future work will have to explore more complex routes with multiple turns under more complicated road conditions.

8 CONCLUSION

In this paper, we investigated three levels of realism in combination with four levels of control over cycling in VR bicycle simulators. To this end, we conducted a controlled experiment with indoor and outdoor settings that focused on three main aspects: (1) realism, (2) safety, and (3) motion sickness. We found that the setup without a bicycle (bikeless) provided the highest sense of cycling safety and a sense of cycling despite the absence of a bicycle. In addition, we found that the setup with a bicycle moving through space (the tandem) produced a high level of realism in cycling without increasing motion sickness. Finally, control over steering and pedaling results in the highest control over cycling for all three bicycle configurations.

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