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ABSTRACT

This study investigates the combination immersive virtual reality (VR) and an instrumented cycling simulator for in-depth behavioral studies of cyclists. To this end, a cycling simulator was developed, virtual environments resembling Singapore were created, combined with the output of a traffic microsimulation. This set-up was created with the specific objective of evaluating the effects environment properties and road infrastructure designs on cyclists' perceived safety. Forty participants, mainly university students, were recruited for the experiment. Results showed that the average speed of the participants changes between scenes with different bicycle facilities, with the highest value for the segregated bicycle path. The braking and head movement activities also changed within each scene, where they significantly occurred more before arriving at the intersections. Questionnaire results revealed adding a painted bicycle path to a sidewalk increases the level of perceived safety. Moreover, participants felt safest for cycling on the segregated bicycle path, in line with findings from previous research. This study provides evidence that cyclists' behavior and perceptions in VR is very similar to reality and that VR, combined with a cycling simulator, is suitable to communicate (future) cycling facilities.

INTRODUCTION

Bicycle mode share in Singapore is rather low and stands at 1%, as compared to Copenhagen with 35% or Amsterdam with 27%. Singapore's National Cycling Plan aims to build more than 700km of cycling lanes by 2030 to increase bicycle ridership *(1)*. Given the low bicycle mode share, and the fact that cyclists' are vulnerable road users, it is necessary to investigate cyclists' preferences and behavior to better understand preferences for cycling facilities. However, due to scarcity of appropriate bicycle infrastructure and relatively low cycling experience in Singapore, any random sample investigating cycling preferences is unlikely to yield valuable results.

Existing studies on cyclists' behavior mainly focused on identifying individual and environmental factors, e.g. gender, age, bicycle facilities, and road hazards, etc. on cyclists' perceptions and decisions through either subjective or objective measures. Subjective measures are generally obtained from self-reported data or surveys that gauge the respondents' subjective perceptions of the environment, while objective measures are typically obtained from field audits or existing spatial data *(2–9)*. Discrepancies exist between the objectively-measured and stated perceptions of the built environment *(10–12)*. While most cycling travel behavior studies rely mainly on objectively-measured attributes, inclusion of subjective measurements is recently proposed by researchers to explain more of the variance in cycling behavior *(13)*.

A second contrasting approach can be found in the approach used to assess cyclist's preferences. Whereas naturalistic approaches investigate cyclists in their natural environment, e.g. in the real world, non-naturalistic approaches study cyclist's preferences in a laboratory environment. The advantage of the latter approach is that subjects can be exposed to environments that they are not familiar with in a controlled environment.

For a cyclist, a non-naturalistic environment could consists of a cycling simulator and a virtual environment showing different cycling facilities. While the usage of driving simulators is well established, less research has been conducted using cycling simulators. Previous research has evaluated the validity of a cycling simulator as compared to cycling in real-life through measures such as speed *(14)* and the choice of speed in different virtual environments through a keyboard controlled environment *(15)*.

The study at hand evaluates the usage of an instrumented cycling simulator and immersive virtual reality to investigate cyclists' perceived level of safety by evaluating the choice of speed, and other measures, in several virtual environments. Furthermore, factors influencing cyclists' perception of safety, including volume and proximity of pedestrians and vehicles are investigated. As compared to previous studies, this study focuses on investigating perceived level of safety in a range of virtual environments using self-reported preferences and cycling behaviour.

The next section continues with a review of literature. Afterwards, the materials and methodology used for this study are presented. The paper continues with the results, and concludes with a discussion and outlook in the final section.

LITERATURE REVIEW

The decision whether to cycle is significantly influenced by the bicyclist's perceived level of safety and comfort *(16–18)*. Two different approaches have been adopted to study cyclists' perceived safety and comfort: naturalistic and non-naturalistic approaches. In a naturalistic approach the subject's behavior is observed in his or her natural environment while cycling, without any significant manipulation or interference. In a non-naturalistic study the subject is analyzed in an artificial setting, or provides data executing an activity that is not cycling; for example, in a laboratory or through a survey *(19)*.

Naturalistic studies have focused on studying cyclists' behavior and preferences by analyzing videos or collecting data of actual conditions. This approach for collecting data to investigate cyclists' perception of safety and comfort has been validated by using two cameras (forward view and cyclist's face), a GPS, and sensors to collect handlebar movement, brake force and speed to collect data *(20)*. Each participant was asked to ride the bicycle for two weeks and at least 40 minutes. Subsequently, safety relevant events were identified and summarized sensor data showed how they were associated. A platform to collect video data was integrated with sensors to collect the cyclists position, and a bio-physiological sensor to measure electrodermal activity (EDA) as an indicator of stress level *(21)*. Based on this real world application, it was found that cyclists experience more stress levels during peak hours and at signalized intersections, while separated bicycle infrastructure revealed to have the lowest stress levels.

Bikeability was studied with an electroencephalography (EEG) sensor measuring variability in mental status, eye tracking which allowed for recording eye movement and the entire visual perception of the user, and an anemometer *(22)* . This research aimed to overcome the false statements of classic qualitative assessments due to selective perception of participants by combining traditional survey methods and new sensor technologies. However, in this naturalistic approach it was difficult to maintain consistent environment properties and similar traffic situations for every participant, and also to obtain reliable bio-physiological sensor measurements.

Most non-naturalistic studies employed surveys to understand cyclists' preferences of environment, route choice, and perceived safety or comfort levels. The subjects evaluated different environments by looking at pictures or short videos of bicycle facilities and intersections *(18, 22–25)*. However, the concern exists to what extent these visualizations can replicate reality and if eventually the participants can imagine themselves cycling in the given environments. This issue can significantly affect the validity of the results of such studies, especially with regards to perceptions while cycling.

With the emergence of new technologies human perception research experiences a methodical re-evaluation. VR technology enables researchers to immerse participants of an experiment into a detailed simulated scene to better inspect the causes and effects of a phenomena. There have been endeavors to create VR cycling simulators for different purposes *(26–28)*, but it is believed that the application of VR can be upgraded as a potential tool to study cyclists' perception of environment and behavior *(29)*. Immersion in VR enables user engagement and allows subjective analysis of participants to better understand their behavior and preferences.

To study cyclist's behavior in simulated road environments, immersive VR has been utilized *(15)*. In this study, a virtual straight path was created, and composed of four different cycling environments. Bicycle movement was translated by arrow keys. Results showed a significant interaction between effects of road type and traffic type. Cyclists on low traffic proved to have significantly higher speed in high traffic areas. The majority of the participants declared that road with a bike lane was their most comfortable cycling environment. They concluded that VR technology can serve as a safe and effective method for in-depth behavior studies.

Simulators have been built for almost all modes of transportation (such as car, train, and airplane) and they have considerably contributed to overall safety. They are capable of creating realistic and complex models of traffic situations under defined laboratory settings and have been widely used for research and training purposes. The use of simulators allow the researcher to have considerable control over the experiment and simulators allow for scenarios to be repeated consistently *(30, 31)*.

However, little research has been done on designing cycling simulators. A cycling simulator surrounded by three projection walls with the objective of generating any desired traffic situation was designed *(32)*. This bike was equipped with acceleration, steering, barking, leaning, and declination sensors and is mounted on a motion platform to simulate the movement of bicycle in a virtual scenario. The system allowed for controllable physical and visual stimuli and facilitated new applications in road safety and neuropsychological research. A second cycling simulator, which allowed for leaning and weaving to study traffic safety and design and evaluation of bicycle facilities *(33)*. The virtual environment was shown through a head-mounted display to provide panoramic 3D space. Position, pedaling, speed, acceleration and braking of the subjects and the other vehicles, leaning angle, traveling direction including weaving angle, and eye-tracking data was used and recorded. The designed system allowed for having two participants cycling in the same VR environment to study interactive cycling behavior and accident analysis.

When it comes to utilizing cycling simulators, it is essential to check the validity of the cyclists' behavior using a simulator compared to cycling in reality. At the same time, the simulator does not have to be identical to the real experience. Nevertheless, it must be able to sufficiently replicate the specific task or behavior that is under investigation *(34)*. Traditionally, simulator validations studies relied on measurements such as speed, speed adaption, lane keeping, and variation in lateral position *(30, 35–37)*.

A cycling simulator was compared with riding on road in a within-subjects study to validate the usage of a cycling simulator *(14)*. These measures focused on spatial positioning, average passing distance from kerbside parked cars, average speed, and speed reduction and head movement on approach to intersections. The on-road bicycle was equipped with sensors to collect GPS coordinates, speed, lateral position from the passing objects on the left hand side, and two cameras to measure the bicycle position within the carriageway and head movements of the participant. The results of this research showed absolute validity was established between riding on-road and using the simulator, regarding lateral position and lateral position variability. Furthermore, relative validity between speeds when riding on-road and when riding in the simulator was discovered, with a higher average speed for cycling on-road. However, with regards to head movement participants did not exhibit similar patterns due to constantly changing traffic conditions on-road. They also concluded that the simulator is suitable for comparison studies assessing differences in speed between different scenarios.

A safety training program through an experimental study utilizing a cycling simulator was conducted in Japan *(33)*. The participants were initially instructed about the cycling rules. Then they faced near-collision events created in VR at intersections, sidewalks, and roadway associated with the cycling rules. Finally they were asked about their impressions on each event and if they could relate them to any of the cycling rules. Principle component analysis of the questionnaire results showed the overall sense of discomfort with regards to the handlebars, brakes, pedals, speed, visibility angle, sound, and impression of the events, while the satisfaction scores for the handlebar were the lowest.

MATERIALS & METHODOLOGY

Study set-up

The study consisted of five parts; in three parts, respondents were immersed in virtual reality. In the first part of the study, respondents were asked to read a short text and complete a short questionnaire concerning socio-demographic characteristics, cycling frequency and attitudes towards cycling. The short text served as a baseline for the psychological data collected in the study. Subsequently, respondents mounted the cycling simulator, immersed themselves in virtual reality (VR) and were asked about the distance and speed differences in VR.

After completing the first three parts of the study, respondents were asked to cycle themselves for approximately six times 90 seconds. During the first bicycle ride, participants could familiarize themselves with the cycling simulator in a virtual environment without pedestrians and vehicles. At the same time, this environment served as a baseline for the analysis of psychological data. Afterwards, respondents cycled through five different virtual environments, with five different types of cycling facilities (treatments). These five treatments were: cycling on the sidewalk, cycling on a sidewalk with a painted bicycle lane, cycling on a painted bicycle lane on the road, cycling on the roadside without any bicycle facility, and cycling on a segregated bicycle lane. The sequence of treatments remained in the same order between subjects. With this approach, a within-subjects study design was pursued.

Volumes of pedestrians and/or vehicles were varied between-subjects. Fifty procent of participants were exposed to a low volume of vehicles / pedestrians, while the other half was exposed to a high volume of vehicles and pedestrians.

The entire study was estimated to last 60 minutes per participant.

Respondents

Respondents were recruited on campus through a website offering students one-hour jobs and through flyers distributed on the campus. Respondents were required to be 18 years and over, should be able to cycle and should be right-handed. Furthermore, we called for Singaporean participants, given that we were especially interested in the perception of cycling safety by Singaporeans. Respondents were allowed to wear glasses or contacts and received a S$15 compensation for taking part in the study, regardless whether they completed the study.

Virtual environment

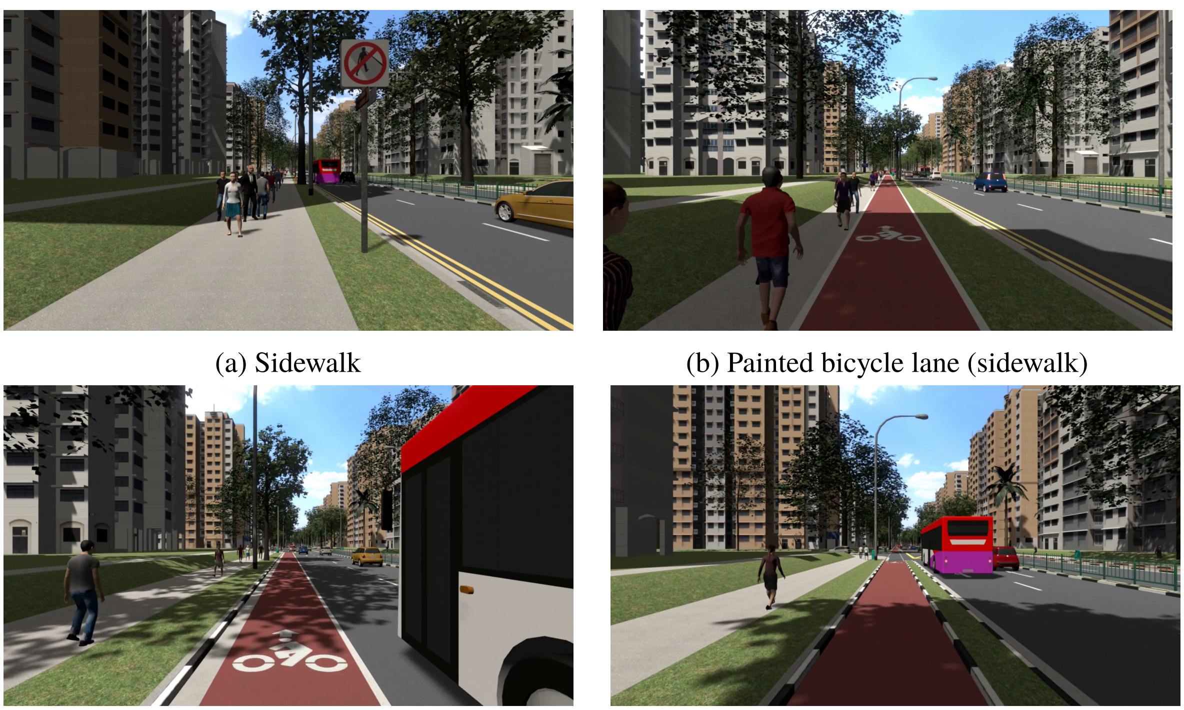
The virtual environments were created with ESRI CityEngine, a software program allowing for parametric designs of streets. The generated environments were exported to Autodesk 3ds Max for post-editing and subsequently to the game engine Unity for further optimization. This pipeline is further elaborated on in *(38)*.

As a basis for the parametric design, a housing estate resembling a typical Singaporean neighbourhood was modelled. Housing estates in Singapore are characterized by high-rise apartments and a combination of two-lane roads and four-lane carriage roads. Commonly in Singapore, cyclists cycle on the sidewalk. Increasingly, sidewalks along central throughfares have a painted bicycle lane on the sidewalk without a grade seperation (e.g. curb). To ease the transition

FIGURE 1 Top view of the parcours

between the real world and the virtual world, subjects see their hands placed on the steering bar; movement of the pedals is synchronized with the position of the legs in the virtual environment.

Participants were wearing a headphone; vehicle sound (buses and cars) was modeled to provide a realistic experience.



(a) Sidewalk (b) Painted bicycle lane (sidewalk)

(c) Painted bicycle lane (road) (d) Segregated bicycle lane (road)

FIGURE 2 Four different treatments

Cycling simulator

Motion control was provided with a instrumented bicycle equipped with a series of sensors; this set-up is outlined in *(39)*. Summarizing, a regular bicycle is equipped (1) a rotation sensor on the pedals, transmitting the movement of the legs to VR for a more realistic experience, (2) a rotation sensor on the wheel, to measure speed and acceleration, (3) a rotation sensor for tilting, to provide extra sensing for the steering and (4) a HTC Vive controller for steering. Each rotation sensor consists of a small microcontroller (Adafruit Feather 32u4), a gyroscope (MPU6050), Bluetooth (Adafruit EZ-Link) and a Li-Ion battery.

For this experiment, the set-up has been slightly changed: the HTC Vive controlled, used for steering, has been replaced by a rotation sensor; the titling sensor has been moved to the brake. Steering was disabled on the bicycle as other VR experiments in our lab had shown that steering created severe motion sickness.

The cycling simulator is placed on Tacx bicycle stand, which provides resistance during cycling; this resistance is not dependent on the speed of cyclists but remained constant.

Immersive virtual reality was provided by a head-mounted display (HMD); for this experiment a HTC Vive has been used. This HMD provides positional tracking; the virtual environment is rendered based on the position of the respondent, thus reducing motion sickness and providing a more realistic VR experience. Furthermore, it allows respondents to wear glasses.

Traffic microsimulation

Pedestrians and vehicles have been simulated with the traffic microsimulation PTV Vissim. For each treatment, two scenarios have been created with different volumes of pedestrians and/or vehicles. More specifically, for the scenarios where the respondent is cycling on the sidewalk the volume of the pedestrian has been varied between-subjects; in the other treatments, the volume of the vehicles has been varied between 500 vehicles per hour and 1500 vehicles per hour. In each treatment, a bus passes the respondents every 20 seconds on the left lane (the lane closest to the respondents.) Participants were able to see a turning car at the intersection at the midpoint in the parcours; this has been done to make respondents aware of the possibility of turning vehicles. Special attention has been paid to creating pedestrian trajectories with more randomness than commonly found in traffic microsimulation models. Invisible objects have been created on the sidewalk for pedestrians to avoid, thus creating movements towards the respondents. Also, pedestrians were standing still at several points in the parcours, to create an element where respondents did not know what to expect what a pedestrian would do next.

At no point in the experiment a collision between the respondent and simulated vehicles and pedestrians could occur. The used version of PTV Vissim (Version 9), however, allows for interaction between the first player (i.e. respondent) and other vehicles in the simulation. However, no use has been made of this functionality for this experiment. Rather, to be able to replicate the same vehicle simulation for all respondents, vehicle trajectories have been exported from PTV Vissim and imported into Unity. These scripts are publicly available in our code repository[1].

[1] https://github.com/fcl-engaging-mobility/UnityScripts

Data collection

Questionnaire

As highlighted earlier in this section, respondents were asked to fill in a questionnaire prior to immersing themselves in VR. For the first two VR experiments, respondents remained seated on the bicycle while answerings questions verbally. In the third VR experiment, where respondents were cycling themselves, respondents dismounted the bicycle after every treatment to answer a series of questions concerning their perception of safety and their willingness to cycle.

Cycling simulator

Data on braking, pedal movement and speed was collected directly from the cycling simulator for every quarter of a second. Head pitch, roll and yaw is recorded from the HMD.

Physiometric data collection

To record the stress levels of participants, respondents were asked to wear a research grade psychophysiological monitoring device, Empatica E4 wristband. The wristband includes a skin-conductance sensor measuring electrodermal activity (EDA) by passing a minuscule amount of current between two electrodes in contact with the skin, a sensor measuring blood flow, heart rate and heart-rate variability and a skin temperature sensor. While this data was collected, the results presented in this paper will not explore this further.

RESULTS AND FINDINGS

Sample

The characteristics of the sample are presented in Table 1. Participants recruited for this study included 40 people (20 female, 20 male). The age of the majority of the participants falls between 18 to 24 (Mean = 25.00; SD = 5.78), reflecting the fact that participants were recruited on campus. Approximately 35% of the participants declared that they own a bicycle and 68% of the participants revealed using any of the bike sharing systems in Singapore.

TABLE 1 Survey sample

	Frequency	Percentage
Gender		
Female	20	50
Male	20	50
Age		
18 to 24	28	70
25 to 34	8	20
35 to 44	3	7
45 to 54	1	3
55 to 65	0	0
Race/Ethnicity		
Chinese	37	92
Malay	2	5
Other	1	3
Education		
Polytechnic	2	5
Post-Secondary (Non-Tertiary)	14	35
Secondary	1	3
University	17	42
University Postgraduate	6	15
Bicycle availability		
Bicycle ownership	14	35
Bike sharing usage	27	68

Perception of safety

Participants were asked questions regarding their perceptions in VR after each of the five scenes. These likert-scale questions ask about safety perceptions due to proximity to / volume of the pedestrians and vehicles. Another question also asks if they were concerned about the pedestrians and/or cars possibly entering their path. Participants responded from totally disagree (point 1) to totally agree (point 7) to each question. The questionnaire results are presented in Figure 3.

Average answers to the perception of safety questions shows how the safety concerns are rooted to the existence of pedestrians and vehicles while cycling on the sidewalk and street, respectively. For instance, 78% of the participants felt unsafe due to proximity to pedestrians and the number of pedestrians while cycling on the sidewalk (they answered 1, 2, or 3 to the corresponding likert-scale questions). However, just by adding a painted bicycle path on the same sidewalk, safety concerns due to proximity to pedestrians and number of pedestrians has been reduced to 15% and 35%, respectively. Results of cycling on the painted bicycle lane reveals that participants were most concerned about the proximity to vehicles by 38%, followed by volume of the passing vehicles with 25% and occasional vehicles coming to their cycling path by 22%.

Cycling simulator

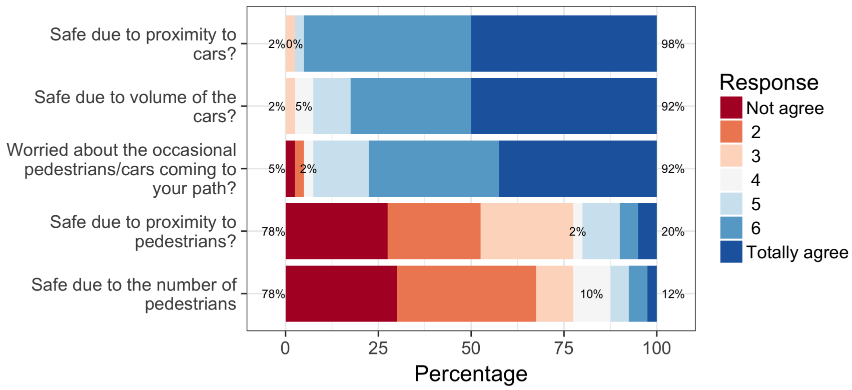
The cycling simulator output is recorded for every fourth of a second. For the analysis presented in this section, the output of the cycling simulator was aggregated in several distance based segments. These distance bins for these segments were determined after inspecting the output data visually. These segments are:

1. The first segment, within 50 meters of starting, is the acceleration segment where participants start and accelerate.
2. The second segment, where participants will maintain their speed, is defined to start 50 meters after starting and end 120 meters from the start.
3. The third segment, approximately 30 meters before the intersection. This is when the intersection becomes visible.
4. The fourth segment, at the intersection, and 30 meters afterwards.
5. The fifth segment starting after immediately after the fourth segment and lasting for 150 meters.
6. The sixth segment, which is defined as 30 meters from the finish line.

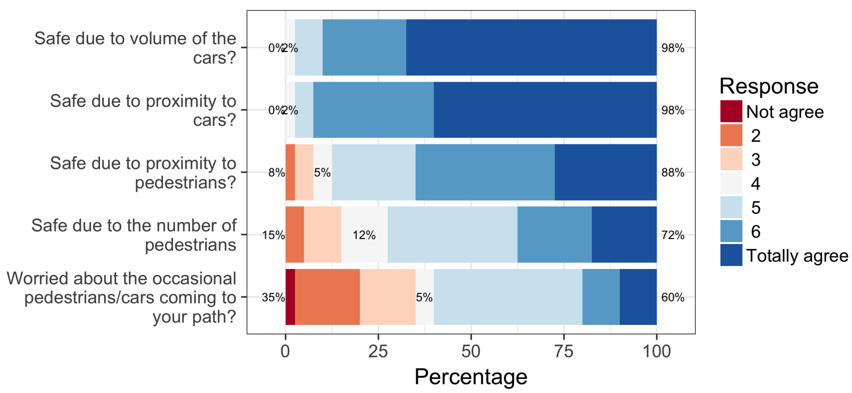
In Table 2 key performance metrics are presented per segment and per treatment. These metrics are the mean speed, the mean braking, and the mean headyaw (turning) to the left and right. It can be seen that the mean speed per treatment differs. Whereas participants cycle on average 15 km/h on the sidewalk, on a segregated bicycle path the speed is 22.5 km/h. Differences between segments are less clear; no speed drop can be observed before or at the intersection. For braking, on the other hand, a clear difference can be observed between the segment before the intersection and the other segments. However, no difference can be observed between the different treatments.

Traffic in Singapore drives on the left side of the road. Furthermore, while driving on the road, cyclists have right-of-way. Pedestrians and cyclists on the sidewalk, however, have to wait for turning cars. Hence, a head turn to the right is expected, and to a lesser extent to the left. For this analysis, the average head position to the right and left is calculated based on the position of the head-mounted display. For all treatments, a clear turn to the right can be observed, and to a lesser extent to the left. The fact that head turning occurs at all treatments, could indicate that participants still expect traffic, despite the fact that this did not happen. Interestingly, participants seem to turn their head less while cycling on the sidewalk. It is hypothesized that this occurs as participants focus on pedestrians.

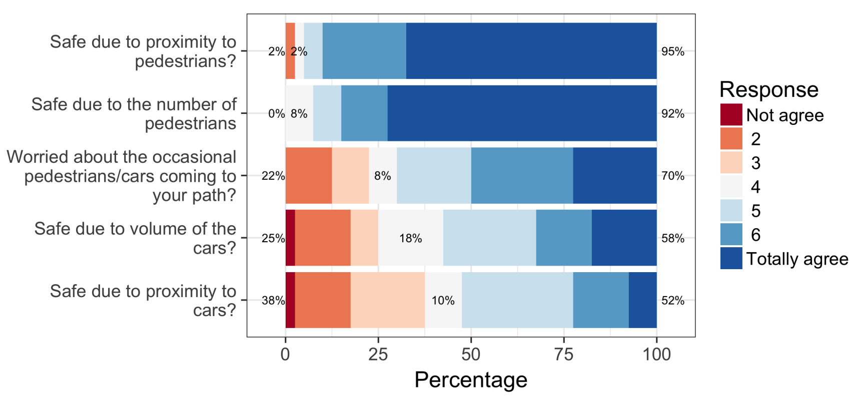
The differences in speed between the different treatments are further analyzed by means of a multi-variate regression. The mean speed per segment is taken as the dependent variable; the different treatments are included as independent variables. Gender is included to correct for any effects arising from socio-demographic characteristics of the participants. The model results are presented in Table 3. Participants consistently cycle faster in virtual environments with cycling



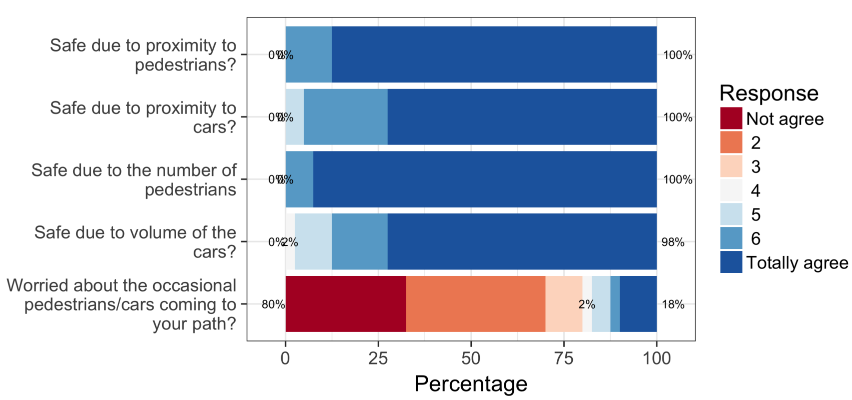
(a) Sidewalk



(b) Painted bicycle lane (sidewalk)



(c) Painted bicycle lane (road)



(d) Segregated bicycle lane (road)

FIGURE 3 Self-reported levels of safety per treatment

TABLE 2 Cycling simulator output per segment

Treatment / segment	Start	Segment 1	Before intersection	Intersection	Segment 2	End
Mean speed [km/h]						
Orientation	11.2	16.5	16.1	17.3	18.5	19.0
Sidewalk	11.4	15.0	15.2	16.4	16.8	16.9
Sidewalk with painted bicycle lane	10.6	20.1	18.1	20.3	21.5	21.0
Painted bicycle path on the road	15.3	21.4	20.3	22.2	23.0	21.8
Cycling on the road	13.3	18.2	19.0	20.6	21.5	20.1
Segregated bicycle path	12.8	22.5	20.7	22.7	24.1	22.6
Mean braking						
Orientation	0.6	0.7	1.0	0.7	0.7	0.7
Sidewalk	0.6	0.8	1.2	0.8	1.0	1.1
Sidewalk with painted bicycle lane	0.5	0.6	1.3	0.6	0.7	1.0
Painted bicycle path on the road	0.5	0.6	1.3	0.7	0.6	1.2
Cycling on the road	0.5	0.5	1.1	0.7	0.6	1.3
Segregated bicycle path	0.5	0.6	1.4	0.7	0.7	1.5
Mean headyaw [left, degree]						
Orientation	5.5	5.2	10.2	4.2	5.6	5.3
Sidewalk	5.2	4.1	6.6	3.7	4.1	3.4
Sidewalk with painted bicycle lane	8.4	3.9	7.9	4.4	3.8	4.7
Painted bicycle path on the road	3.8	5.1	6.4	3.6	3.8	3.6
Cycling on the road	3.1	3.6	6.3	4.0	5.0	3.8
Segregated bicycle path	11.7	5.9	7.4	4.3	4.3	3.9
Mean headyaw [right, degree]						
Orientation	5.2	7.2	12.9	4.9	6.6	8.7
Sidewalk	2.7	3.4	12.4	2.8	2.8	2.2
Sidewalk with painted bicycle lane	8.0	4.0	16.7	3.3	3.9	2.8
Painted bicycle path on the road	8.1	7.8	17.8	7.9	4.7	6.1
Cycling on the road	5.8	6.9	13.2	4.1	6.7	4.4
Segregated bicycle path	9.2	5.5	19.5	6.7	4.4	6.3

facilities as opposed to cycling on the sidewalk. Moreover, participants cycle faster when a painted bicycle lane on the road is provided as compared to simply cycling on the road without facilities.

Headyaw and braking per segment are further analyzed by means of a regression model; model results are presented in Table 4. For this analysis, the different segments are entered as dependent variables. Model results show that participants significantly turn their head to the right, and to a lesser extent to the left, prior to the intersection. Also, participants brake more prior to the intersection.

TABLE 3 OLS results for mean cycling speed [km/h] per segment for selected segments

Coefficients	Segment 1			Before intersection			Intersection		
	Est.	t-test	Sign.	Est.	t-test	Sign.	Est.	t-test	Sign.
Intercept	15.42	20.58	***	16.14	24.09	***	16.57	24.34	***
Treatment									
Sidewalk [reference]	-	-	-	-	-	-	-	-	-
Sidewalk with painted bicycle lane	4.66	4.79	***	2.57	2.74	**	3.71	4.20	***
Painted bicycle path on the road	5.77	5.97	***	4.85	5.19	***	5.70	6.49	***
Cycling on the road	4.54	4.70	***	4.10	4.38	***	4.52	5.15	***
Segregated bicycle path	6.99	7.28	***	5.41	5.83	***	6.27	7.19	***
Socio-demographics									
Male	1.66	2.73	**	-	-		1.16	2.10	*
Adjusted rho-square	0.25			0.17			0.25		

Sign. codes: 0 *** 0.001 ** 0.01 0.05 . 0.1 1

TABLE 4 OLS results for selected performance measures

	Mean headyaw [left, degree]			Mean headyaw [right, degree]			Mean braking		
	Est.	t-test	Sign.	Est.	t-test	Sign.	Est.	t-test	Sign.
Intercept	4.11	17.77	***	5.77	7.17	***	0.69	15.33	***
Segment									
Segment 1	-	-		-	-				
Before intersection	3.80	7.35	***	11.45	6.39	***	0.55	6.11	***
Intersection	-	-		-	-		-	-	
Segment 2	-	-		-	-		0.45	4.92	***
End	-	-		-	-		-	-	
Adjusted rho-square	0.21			0.17			0.20		

Sign. codes: 0 *** 0.001 ** 0.01 0.05 . 0.1 1

DISCUSSION & OUTLOOK

Discussion

This study aimed to investigate the capability of combining immersive virtual reality (VR) and an instrumented cycling simulator for in-depth behavioral studies of cyclists. To this end, a cycling simulator was developed *(39)*, virtual environments resembling Singapore were created, combined with the output of a traffic microsimulation. This set-up was created with the specific objective of evaluating the effects environment properties and road infrastructure designs on cyclists' perceived safety.

By conducting a controlled experiment with 40 participants, the influence of cycling environment on cyclists' behavior and perceptions was explored. The measurements include position, speed, pedaling, braking, head yaw and head pitch movements. This experiment showed that the cycling simulator captures behavioral differences between treatments and demonstrated how cycling behavior in virtual reality is similar to reality.

The overall average of the self-reported answers of the individuals to the safety questions explains how participants felt most safe cycling on the segregated bicycle path, which is aligned with the results of the previous studies in the literature *(19, 40, 41)*. However, the introduction of a painted bicycle path on the sidewalk showed how the participants felt safer and they were less worried about the pedestrians.

Environmental factors such as cycling facility type proved to influence the average speed of the participants. The whole length of the cycling path is divided into segments to better analyze measurements such as speed, braking, and head movement. It was found that the average cycling speed on the segregated bicycle path was higher than other cycling facilities, which can be an indicator of the higher confidence and safety perception of the participants in this design. In a previous study it was found that cyclists cycle faster on a bike lane as compared to on a shared lane with vehicles *(15)*; in this study motion was provided with a keyboard (e.g. arrow keys). The order of magnitude between cycling speeds on different cycling facilities is larger than previously found, and varies between 15 km/h and 22km/h, which, to the authors, seems as realistic choice of speed. For instance, it was found that respondents cycle 4.6 km/h faster on a painted bicycle lane on the sidewalk as compared to the cycling on the sidewalk without any cycling facilities. This could be because respondents were less worried about conflicts with pedestrians. However, from a pedestrian perspective a higher speed of cyclists would not be desirable without horizontal separation or vertical separation.

Analysis of the head movement data showed how the mean head movement in all of the designs right before the intersection, mainly to check for the existence of turning cars, similar to previous findings comparing cycling in reality and cycling in virtual reality *(14)*. Descriptive analysis revealed that head movement is less while cycling on the road. This could be because participants assume that car drivers notice them while cycling right next to the traffic stream, and because cyclists have right-of-way while cycling on the road, but not when cycling on the sidewalk.

Outlook

The sequence of the scenes was selected in such a way to account for the availability of a bicycle facility and the proximity to the sidewalk. Given that cyclists in Singapore would be familiar with cycling on the sidewalk, the participant was placed on the sidewalk first. This ordering helped better observe the influence of the bicycle facility on participants behavior. However, the effects of the gradual familiarity with the cycling simulator needs to investigated further. Therefore, a certain number of the future experiments will be conducted with a different sequence to investigate whether ordering and learning effects occur.

As a next step, detailed models will be constructed to investigate the relationship between cycling behavior and the proximity to pedestrians and vehicles. Furthermore, physiological data will be analyzed to investigate the influence of environment properties on the stress levels of the participants. This analysis will be compared against the participants' self-reported perception of safety.

Speed performance and bike lane position and are two key metrics for cyclist riding performance evaluation *(15)*. One of the limitations of this study was the locked steering which confines riding to a straight line. The steering wheel sensor was deactivated after motion sickness was observed during the pilot tests. It was also noticed that maintaining position in VR requires a lot of attention, distracts the participants, and does not allow them to focus on the experiment's points of interest.

Another limitation was the lack of interaction between the participant (as the cyclist in VR) and other road users, due to technological limitations. The latest version of the PTV Vissim has offered Unity integration and allows for online control of the agent in Unity. This functionality can improve the existing model building pipeline which eventually enhances user experiences, yet to be further investigated. Furthermore, other sensors such as eye tracking sensor can be added to this experiment to further explore the points of gaze of cyclists, especially at the unsafe locations, such as intersections.

Given the promising results so far, a cycling simulator combined with immersive virtual reality is seen as a promising avenue to communicate future street designs.

AUTHOR CONTRIBUTION STATEMENT

Mohsen Nazemi did the traffic simulation and collected the experiment data; Mohsen Nazemi and Dr Michael van Eggermond conducted the data analysis and have written the manuscript. Dr Alex Erath conceptualised the study and designed the experiments. Prof Kay. W. Axhausen provided feedback on the study design, questionnaire and results. All authors reviewed the results and approved the final version of the manuscript.

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