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Research article

What turns a bicycle street into a street for cyclists? A multimodal study on subjective safety of infrastructure measures on bicycle streets using an approach in virtual reality

Marc Schwarzkopf[1*], **André Dettmann**[1], **Angelika C. Bullinger**[1]

[1]Chemnitz University of Technology, Germany

[*]Corresponding author: marc.schwarzkopf@mb.tu-chemnitz.de

Guest editor: **Arend Schwab**, Delft University of Technology, the Netherlands

Reviewers: **Felix Wilhelm Siebert**, Technical University of Denmark, Denmark
Carmelo D'Agostino, Lund University, Sweden

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Abstract: In an increasingly urban and sustainable transportation-focused world, cycling emerges as a key environmentally friendly and health-promoting mode of travel. This paper addresses the gap in understanding cyclists' subjective safety, particularly in relation to bicycle streets in Germany. Utilizing a multimodal approach, two studies were conducted: an online questionnaire (Study I) and a Virtual Reality (VR) evaluation (Study II), focusing on the Reichenhainer Straße in Chemnitz. Study I involved N = 182 participants who regularly used the bicycle street. The questionnaire covered various aspects including mobility behavior, cycling experience, and subjective safety, using a 6-point Likert scale. Infrastructure characteristics were represented through images. Results showed that participants generally felt safe on the bicycle street, with key factors being the lane width and restrictions on motorized traffic. Study II, a pioneering effort in using VR and stereoscopic 360° images for evaluating cycling infrastructure safety, involved N = 32 participants. It provided a realistic evaluation of infrastructure elements and their impact on perceived safety. The study revealed significant differences in safety ratings based on the presence of cars and cyclists' experience levels. The use of VR allowed for a focused examination of infrastructure characteristics and their perceived safety, highlighting potential areas for improvement. Both studies demonstrated consistent results, underscoring the subjective safety of the Reichenhainer Straße, which was perceived as safer than the average bike-accessible infrastructure in Chemnitz. The VR method proved effective for detailed evaluation of subjective safety, independent of participants' familiarity with the specific infrastructure. This approach offers a structured, controlled, and resource-efficient way to evaluate cycling infrastructure under laboratory conditions. In conclusion, the findings align with existing literature and emphasize the importance of lane width and reduced motorized traffic for cyclists' safety. The innovative VR method, while still developing, offers promising implications for future citizen participation initiatives and infrastructure planning projects, enabling efficient post-completion evaluations of subjective safety. Such practices are rare in German planning offices, highlighting the paper's contribution to enhancing urban cycling infrastructure planning and safety assessment.

Keywords: cyclist perception, extended reality infrastructure, subjective safety, validity, virtual reality

1 Introduction

In a world increasingly shaped by urban mobility and sustainable transportation, cycling is gaining more and more importance as an environmentally friendly and health-promoting means of travel. According to the results of the Bicycle Monitor (Sinus Institut, 2021), cycling has the highest growth potential compared to other modes of transportation in Germany. In addition to the steadily increasing number of cyclists, the sense of safety among them while using bicycles increased by the year 2021 compared to the reports of 2017 and 2019 (Sinus Institut, 2021). Subjective safety is an important concept as it influences the decision to choose cycling as a mode of transportation (Sanders, 2013). In general, 63% of cyclists in Germany reported feeling very or somewhat safe (2021: 63%, 2019: 56%, 2017: 53%), still, around a third of cyclist in Germany fells unsafe or very unsafe (Sinus Institut, 2021). Speed limits for motorized vehicles and their presence on or directly next to bicycle infrastructure have the greatest influence on this perception of safety (Sørensen & Mosslemi, 2009; Vandebona & Kiyota, 2001). So, a lack of dedicated bicycle lanes might contribute to this feeling as well since they can make biking more comfortable, quicker, and safer (Monsere et al., 2014), but their effectiveness largely depends on their design quality and road environment, which is constrained by regulatory uniformity.

Analyzing the road environment and infrastructure characteristics is crucial for both the objective and subjective safety of cyclists. The 'road environment' encompasses all physical and traffic-related features, including traffic volume and composition, infrastructure characteristics and environmental conditions. Together, these elements determine how safe and comfortable cyclists and other road users can navigate the road (Meuleners et al., 2019). Infrastructure elements significantly impact perceived safety. Cyclists feel safer on routes with dedicated bike lanes, traffic calming measures, and residential streets, while high-risk perceptions are linked to major streets without bike infrastructure and areas with high vehicle interaction (Manton et al., 2016). Cyclist safety perceptions are influenced by road type, presence of bike lanes, and vehicle interactions. Cyclists report feeling unsafe on roads without bike lanes and near large vehicles, underscoring the need for safer road designs (Beck et al., 2021). In Germany this is mirrored by cyclists who wish more bikes lanes (56%), better separation from car traffic (50%), and more cyclist-friendly streets (39%) (Sinus Institut, 2021).

Bicycle lanes are also an opportunity to increase safety, as they are used exclusively or mainly by cyclists and offer significant safety benefits and are strongly preferred by users (Lusk et al., 2011). They promote the use of bicycles as a sustainable mode of transport and help to reduce traffic risks (Tsubohara, 2015; Blitz et al., 2020). However, conflicts with motorised traffic and inadequate design can reduce the acceptance and effectiveness of such measures (Blitz et al., 2020). For example, a study in the Rhine-Main region, Germany, found that the introduction of cycle lanes had a positive impact on the use of bicycles, while the reduction in car use was limited.

In Germany, a bicycle street is a designated road for bicycle and E-Scooter traffic. According to a survey by the German Federal Ministry of Transport and Digital Infrastructure (BMDV, 2021), 39% of respondents listed 'more bicycle routes' as the most urgent demand for the government. Hence, bicycle streets need to become an important element in bicycle traffic planning to increase the safety and attractiveness of cycling in Germany (BMDV, 2021). To accomplish this, cars and other vehicles are allowed but with speed restrictions and special rules to increase the attractiveness and safety of cycling and create advantages over motor vehicle traffic. Other European countries have similar infrastructure measures, e.g. in the Netherlands, so-called 'fietsstraaten' (bicycle streets) are established, which are shared by bicycles and cars but give priority to bicycles, are a common practice. These roads have proven to be effective in reducing the speed of cars and increasing the safety of cyclists (Tsubohara, 2015).

Currently, about 96% of German bicycle streets allow motorized traffic (ADFC, 2022). Moreover, the establishment of bicycle streets is governed by technical regulations based on objective safety analysis, often overlooking cyclists' subjective safety (Gössling & McRae, 2022; Schwedes et al., 2021). Bicycle streets in Germany are built based on recommendations (Alrutz, 2011), some of which are viewed as outdated, and the experiential knowledge of planners, who typically do not evaluate completed infrastructure projects for their perceived safety (Schwarzkopf et al., 2023). This can result in infrastructures that are safe in objective terms but do not feel safe to cyclists, deterring bike usage (Hull & O'holleran, 2014; Wang et al., 2014). One way to make infrastructure more user-centred is to introduce a method that enables urban planners to involve the public more, taking into account the (road) environment and make planning more transparent (Wolf et al., 2020).

In the last decade, an increase in the use of Virtual Reality (VR) in infrastructure design and urban planning has been observed. VR has been successfully used in the area of citizen participation for construction projects, also infrastructure, buildings and green spaces have been planned with the help of VR (Wolf et al., 2020; Mahbubur & Kitson, 2020; Zhang et al., 2020). VR can also be used early in the planning stage to evaluate the impact of infrastructure on safety, comfort, and (dis-)satisfaction (Wolf et al., 2020; Schwarzkopf et al., 2023). VR offers several advantages compared to previously used evaluation methods in urban planning (e.g. inspections, on-site surveys): Besides providing a more motivating and realistic evaluation of infrastructure, it can be employed anywhere due to its integrated computing units (Wolf et al., 2020). Furthermore, an evaluation of the perceived safety of cycling infrastructure is generally not carried out by planners, as on-site inspections and surveys are considered too time-consuming and therefore also resource-intensive (Schwarzkopf et al., 2023). Accordingly, the user's perspective is generally not taken into account when planning and evaluating infrastructure projects in Germany. The capabilities of VR technology could be used, among other things, to evaluate the perceived safety of (cycling) infrastructure in a resource and time-efficient manner, as it is suitable for replacing or supplementon-site surveys. Furthermore, multiple (cycling) infrastructure measures could be sequentially evaluated in a short time under controlled conditions, even if the person who evaluates the infrastructure does not know it in real life (Wolf et al., 2020; Schwarzkopf et al., 2022). This also opens up the possibility of simulating traffic situations that demonstrate safety-critical behavior and making them accessible to the test subjects without endangering them (e.g. in the case of critical overtaking maneuvers). In summary, VR can help to bring the user's perspective into infrastructure planning and give subjective factors (e.g. subjective safety) more influence in planning. In addition, critical traffic situations can be easily simulated without putting the test subjects in danger, which also opens up the possibility of interviewing the group of people who refrain from cycling due to safety concerns.

VR can also contribute to closing some research gaps in the field of bicycle streets: There is little research on how specific environmental factors of bicycle streets affect subjective safety, there is a lack of data on whether bicycle streets shared with cars under certain conditions improve perceptions of safety, and the focus is usually on active cyclists, ignoring those who do not cycle frequently for safety reasons. But, above all, the evaluation of subjective safety is rarely or not at all of interest to those who bear a significant portion of the responsibility for infrastructure design: the planners and authorities. In this paper, we have two goals: First, we aim to address these issues by adopting a multimodal approach. The second goal is to test a prototype for evaluating the perceived safety of cycling infrastructure with static, stereoscopic images in VR.

In study I, we employ an online questionnaire to assess the perceived safety of a selected bicycle street in Chemnitz (Reichenhainer Straße) that has through traffic. This study additionally investigates how the street environment, in this case: infrastructure elements, street condition and associated rules, are evaluated in terms of perceived safety. In study II, we use a VR approach to evaluate perceived safety on the same bicycle street and the rating of the subjective safety of its street environment as well. For this purpose, static, stereoscopic images are presented in a self-developed VR application.

2 Method

For both studies, it was initially essential to identify infrastructure elements and safety habits relevant to cyclists. To this end, relevant elements were first extracted from the literature (Manton et al., 2016; Lawson et al., 2013) and the 'Empfehlungen für Radverkehrsanlagen' (Recommendations for Cycling Infrastructure) ERA 10 (Alrutz, 2011) which is a widely used basis for bicycle infrastructure planning in Germany. The infrastructure elements listed in the ERA-10 are intended to contribute to the (objective) safety of cycling infrastructure. Subsequently, an onside walkthrough on the bicycle street was conducted with a group of N = 7 cyclists and N = 2 urban planning experts to identify important infrastructure characteristics for the perceived safety of cyclists. The total set of identified infrastructure characteristics was then discussed and categorized in a focus group of N = 4 experts from the fields of cycling safety and urban planning. Additionally, possible implementations of further elements (e. g. bumpers; if urban planning permits), rule-based (e.g. allowed maximum speed) and condition-based (e.g. traffic volume) influences were also considered. This set of street environment characteristics was either fully (study I) or partially (Study II) utilized in both studies (refer to Table 1). Content that could not be equally represented in both the online questionnaire and the VR study was not considered (e.g. the priority of cyclists over other road users).

Table 1 List of identified relevant streetenvironment characteristics for the Reichenhainer-Straße bicycle street used in Study I

Existing elements	Possible elements	Rules	Condition
Color highlights*	30 km/h traffic signs	Driving side by side	Parking cars*
Curbs*	Speed bumbs	Max. speed of 30km/h	Presence of cars*
Paved safety strip*	Speed traps		Road width*
Traffic lights*			Surface condition*
Traffic signs*			Traffic volume (decreased)*

* used characteristics for Study II

The ADFC (2022) Bicycle Climate Test for Chemnitz was used as the measurement tool for general subjective safety while cycling in both studies. It originally includes seven items related to subjective safety. For the survey on the bicycle street, these items were slightly modified to maintain comparability with the 2020 Bicycle Climate Test for the Chemnitz area (ADFC, 2022), we ignored an item that revolves around the topic of bicycle theft. The answers were assessed using a six-point Likert-scale (1—totally agree, 6—totally disagree). The items used are displayed in Table 2.

We opted for two studies to achieve both a general overview with as many participants as possible (Study I) and to take a more detailed look at individual infrastructure characteristics, as well as to test a new method in VR (Study II).

Table 2 List of items to determine the perceived safety of the entire cycle lane

On the bicycle street Reichenhainer Str…
... you feel safe as a cyclist.
... there are rarely conflicts between cyclists and pedestrians.
... there are rarely conflicts between cyclists and motorists.
... there are no obstacles on the street.
…is designed so that young and older people can cycle safely.
... you can cycle quickly and safely on the road together with the cars.

1. Items were adapted on the basis of ADFC (2022).
2. Participants were asked to rate their agreement with the statements on a six-point Likert-scale.

3 Analysis

In this section, we briefly summarize the analyses we are planning for the collected data. For both studies (online questionnaire and virtual reality), the first step is to determine how the respondents rate the perceived safety of the cycle lane and compare the result with the general assessment of cycling infrastructure in Chemnitz by the Allgemeiner Deutscher Fahrradclub (ADFC, 2022). Individual infrastructure elements and rules are then assessed in terms of their perceived safety, as we want to identify which elements or rules increase the perceived safety of the infrastructure. In addition, it is also analyzed how well respondents rate the form of presentation of street environment elements as pictures in an online questionnaire and in VR. Hierarchical regression is then used for Study I to analyze whether the evaluated street environment elements have a significant influence on the perceived safety of the bicycle street, e.g. the entire infrastructure. In Study II, we also want to get a first impression of how VR technology can be used as an assessment tool for the perceived safety of cyclists.

3.1 Study I—online questionnaire

Study I consisted of a questionnaire which was provided in an online format and comprised items on the following topics: awareness of the bicycle street, mobility behavior, cycling experience, knowledge of traffic rules on bicycle streets, usefulness, acceptance, subjective safety, and sociodemographic data. The infrastructure characteristics (see Table 1) were presented with two pictures from the bicycle street

Reichenhainer Straße depicting typical scenarios (if possible). Examples are displayed in Figure 1.

For each element of road environment characteristics, participants evaluated whether the respective element increased or decreased perceived safety using a 6-point Likert scale (1—very unsafe; 6—very safe). This data was also used to calculate a hierarchical regression. For this purpose, a G-Power analysis was conducted, selecting a significance level of $\alpha = .05$ with a test power (1-β) of .80 and a small effect size ($f^2 = .02$) for the expected influence of infrastructure characteristics on the subjective safety. This resulted in a minimum sample size requirement of 175 participants. The questionnaire was completed by N = 182 individuals (n = 68 females, M_{age} = 30.33, SD_{age} = 9.34). Only individuals who cycled on the bicycle street at least once a month were eligible to participate. A total of n = 114 participants defined themselves as experienced cyclists. The questionnaire was available online during the month of June 2022. Participants did not receive any compensation for their participation. Test subjects were recruited via a flyer with a QR code and mailing lists.

3.2 Study II—VR experiment

The Study II, a VR study, is based on our previous work (Schwarzkopf et al., 2022). From the infrastructure characteristics listed in Table 1, those from the 'Existing Elements' and 'Condition' categories were implemented in VR. Stereoscopic 360° images of these elements were captured, showing the same elements and comparable contexts as the pictures presented in the questionnaire. These images were then incorporated into a self-developed app and presented randomly. Some of the photos showing vehicles on the road reveal irregular behavior by motorized traffic. Among other things, the pictures show an overtaking situation, which is illegal due to the total width of the road (minimum distance of 1.5 meters from cyclists cannot be maintained during an overtaking maneuver). However, this behavior is very common on the bicycle road and is therefore part of our observations. During the use of the VR headsets, participants were asked to imagine they were cycling. For each of the twelve images, participants evaluated the subjective safety of each of the visible infrastructure characteristics on a 6-point Likert scale (1—very unsafe; 6—very safe) also using thinking aloud. Additionally, participants were asked to explain the reasoning behind their assessments. After viewing all the images, participants rated the subjective safety for the entire bicycle street on a 6-point Likert scale (1—very unsafe; 6—very safe). In contrast to Study I, participants evaluated the current state and assessed how safe they perceived it to be. The procedure is presented in Figure 2. After completing the VR part, a questionnaire was administered to collect demographic data as well as information on bicycle use and experience (identical questions as in Study I) as well as an inventory for affinity for technology (Franke et al., 2018) and the intuitiveness of technology use. In this study, N = 32 (n = 13 females, M_{age} = 26.22, SD_{age} = 3.04) cyclists participated, of whom n = 18 identified themselves as experienced cyclists, n = 11 participants do not use the bicycle street and n = 23 had no prior experience with VR headsets. The experiment took 15–20 minutes to complete. The study took place directly in front of or in the student canteen of Chemnitz university of technology. The test subjects were selected at random and approached before or during lunch. Participation was not remunerated.

4 Results

4.1 Study I

The concept of subjective safety was examined from two perspectives and can be divided into subjective safety regarding road environment characteristics and a general inquiry about subjective safety on the 'Reichenhainer Str.' bicycle street in general. The participants rated the subjective safety of the bicycle street (M = 2.48; SD = 0.79) significantly better than the comparison value of 4.4 (average rating of the Bicycle Climate Test for streets in Chemnitz; $t(182) = -32.19$; $p < .001$; $d = -2.4$) (ADFC, 2022). The results of the evaluation of subjectie safety for individual road environment characteristics can be found in Table 3.

The question of the extent to which the presentation of the infrastructure features as images in an online questionnaire was considered suitable for an evaluation was rated as 'satisfactory' by the test subjects (M = 2.78; SD = 1.24) using a school grading system (1—very good, 6—poor). In the evaluation of individual road environment measures, there was no significant difference between experienced and inexperienced cyclists. Additionally, a regression analysis was conducted to quantify the influence of road environment characteristics on perceived safety. A hierarchical regression was used to examine

Figure 1 Example images shown in the questionnaire (from left to right: road marking (implemented), paved safety strip (implemented), signs (implemented), road marking I (good practice solution), road marking II (good practice solution)

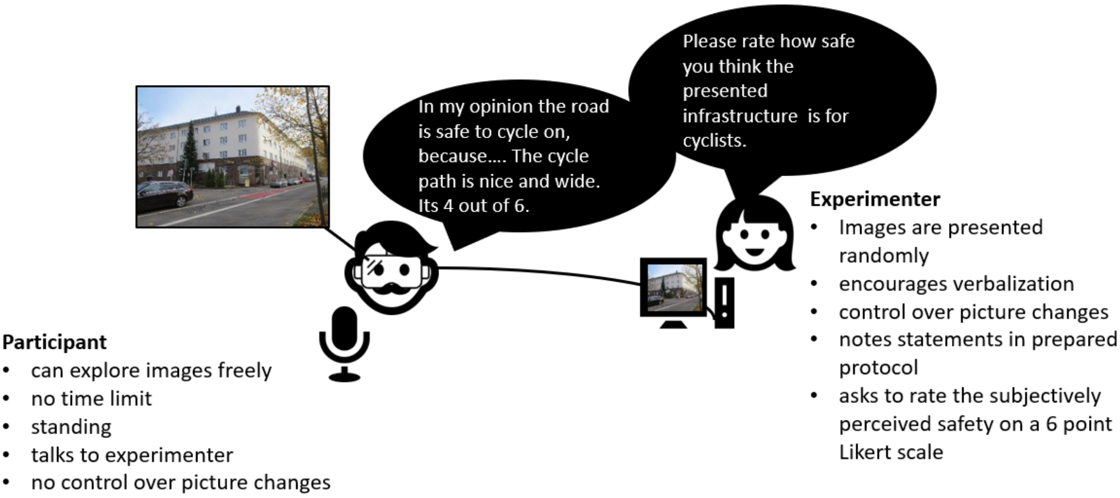

Figure 2 Schematic procedure evaluating the subjective safety of bicycle infrastructure in VR, adapted from Schwarzkopf et al. (2022)

the influence of control variables (age, gender, acceptance) on the investigated relationship. The examination showed that the control variables did not significantly affect the perceived safety of the bicycle road ($F(3, 179) = 1.1$; $p = .41$), so age, gender and the grade of acceptance have no influence of the perceived safety of the bicycle infrastructure in this study. In contrast, the second model, which included the selected predictors displayed in Table 2 (road environment characteristics), was significant ($F(13, 169) = 9.94$; $p < .001$, $N = 182$) and demonstrated that the regression model provided a significant explanatory contribution. Both the multiple correlation coefficient (R = .67) and the corrected coefficient of determination ($R^2{}_{corr}$ = .32) indicating a strong correlation between the predictors and subjective safety. Additionally, the model's high fit with 32% ($R^2{}_{corr}$ = .32) corresponds to a strong effect (f^2 = .47). The variables maximum speed ($\beta = -0.27$; [-0.32; -0.10]) and wider lane width ($\beta = 0.25$; [0.05; 0.19]) emerged as the strongest predictors, being the only ones to make a significant contribution. The participants of the study rated the representativeness of the presentation format in the online questionnaire (two images) as satisfactory (M = 2.78, SD = 1.24).

4.2 Study II

The concept of subjective safety was examined from two perspectives again. It was divided into subjective safety regarding road environment elements (Table 4) and a general inquiry about subjective safety on the Reichenhainer Straße bicycle street. The participants rated the subjective safety of the bicycle

Table 3 Evaluation of subjective safety of individual road environment characteristics using an online questionnaire. Participants rated to what extent each element increases or decreases perceived safety (1—very unsafe; 6—very safe, N = 182).

Infrastructure characteristics (online questionnaire)	M	SD
Decreased traffic volume	4.52	1.55
Maximum speed of 30 km/h	4.51	1.01
30 km/h traffic signs	4.29	1.38
Driving side by side	4.27	1.28
Surface condition	4.26	1.55
No parking cars	4.23	1.72
Road width	4.22	1.62
Speed traps	4.03	1.63
Curbs	3.95	1.32
Paved safety strip	3.77	1.32
Speed bumbs	3.31	1.68
Colour highlighting of the roadway	3.22	1.24
Road lighting	3.13	1.43

street (M = 2.26; SD = 0.82) significantly better than the comparison value of 4.4 (average rating of the Bicycle Climate Test for streets in Chemnitz; $t(32) = -2.89$; $p < .001$; $d = -1.9$.) (ADFC, 2022). There was no significant difference in the subjective safety ratings between participants who use the bicycle street and those who do not. The results of the evaluation of subjective safety for individual infrastructure characteristics can be found in Table 4.

Table 4 Evaluation in VR of perceived safety due to the presence/condition of an road environment element on Reichenhainer-Straße (N = 32).

Infrastructure characteristics (Virtual Reality)	M	SD
Surface condition	5.71	0.65
Color highlighting of the roadway	5.50	0.78
Traffic lights	5.00	1.02
Road width	4.67	1.78
Decreased traffic volume	4.24	1.02
Curbs	4.09	1.18
Paved safety strip	3.75	1.60
Parking cars	3.47	1.29

Furthermore, it was examined whether cycling experience had a significant influence on the ratings for individual infrastructure characteristics. This influence was identified for two elements. Experienced cyclists viewed the paved safety strip as significantly less safe (M = 3.39, SD = 0.92) than inexperienced (M = 4.21, SD = 0.70) cyclists $t(32) = 2.80$; $p < .01$). Additionally, high curbs were also rated as significantly ($t(32) = 2.17$; $p < .05$) less safe by experienced cyclists (M = 3.89, SD = 1.04) compared to inexperienced ones (M = 4.36, SD = 1.3). Additionally, the study also explored whether the presence of cars influenced the rating of infrastructure characteristics. This effect was significant for the condition of the lane width (two conditions, $t(64) = 10.01$; $p < .001$). When a photo showed a car directly in front of, next to, or behind the participant's viewpoint, the street lane width was described as significantly less safe (M = 3.81, SD = 0.78) compared to situations without cars in the immediate vicinity (M = 5.53, SD = 0.62).

The participants rated the representativeness of the infrastructure characteristics depicted in the VR with a score of M = 1.19 (SD = 0.38), using a school grading system (1—very good, 6—poor). Furthermore, there was no significant difference in this rating between participants who use the street and those who do not. The intuitiveness of using the technology (VR headset and app) was rated as very intuitive, using a school grading system as well (M = 1.24, SD = 0.36). No case of motion sickness was observed during the experiment.

4.3 Comparison

Both studies show that the subjective safety of the 'Reichenhainer Str.' bicycle street is rated significantly higher than the subjective safety of the average cycling infrastructure in Chemnitz (Study I: M = 2.48 (SD = 0.79); Study II: M = 2.26 (SD = 0.82) vs. 4.4) (ADFC, 2022). Both studies also provide comparable results regarding the status quo of perceived safety assessments of infrastructure measures. The road environment characteristics that were rated as safe or very safe in Study II did not contribute to an increase in perceived safety in Study I. This indicates that an improvement or more frequent implementation of these infrastructure features, compared to the current state, would not offer added value for perceived safety. However, the VR study shows significant differences in the perception of the subjective safety of some infrastructure measures (curbs, paved safety strip) between experienced and inexperienced cyclists, while the online questionnaire study does not identify such differences. Another difference is the impact of cars on the perception of lane width, which was only examined in the VR study and affected the rating of lane width (when cars were present, the lane width was perceived as too narrow). Regarding the representativeness of the presentation formats, the VR representation (M = 1.19; SD = 0.38) was rated as more representative than the image representation in a questionnaire (M = 2.78; SD = 1.24).

5 Discussion

5.1 Study I

In predicting subjective safety on the Reichenhainer Straße bicycle street, the most significant predictor was the speed limit. The speed limit had a negative correlation with subjective safety. The more unsafe cyclists felt on the bicycle street, the better they rated the safety due to the existing speed limit measure. As found in this study, and supported by literature, speed limits for motorized vehiclesare one of the most crucial factors influencing cyclists' sense of safety (Sørensen & Mosslemi, 2009; Vandebona & Kiyota, 2001). Additionally, the predictor of wider lane width was significant. The safer cyclists felt on the bicycle street, the greater their perception of safety improvement due to the potential measure of widening the lane. This finding aligns with the study by (Radwege Check, 2020), which identified lane width as the most influential factor for perceived safety. Not very surprising, cyclists consider a lower volume of motorized traffic and adherence to the 30 km/h speed limit as important elements for perceived safety. However, elements that provide infrastructural support for these measures, such as bumpers or radar traps, are not perceived as significantly enhancing safety. The data basis in the form of images in the online questionnaire was only rated as sufficient (M = 2.78, SD = 1.24), which could limit the validity of the results. However, the validity of the results is expected to be high since all participants are familiar with the evaluated bicycle street since they used it at least once in the month before the survey.

5.2 Study II

In Study II, participants were virtually placed on the bicycle street via VR, allowing them to examine the influencing factors 'on-site'. Notably, the form of presentation was considered as representative by the participants (M = 1.19; SD = 0.38; 1—very representative, 6—not representative at all), regardless of whether the bicycle street was actually used. Additionally, the technology was rated as intuitive and easy to use. However, the validity must be regarded as limited, as no comparison of the VR assessments with on-site assessments has yet been carried out. In this study, almost all existing road environment characteristics were rated as 'safe' or 'very safe' (see Table 3). Only parked cars and the paved safety strip were not rated as safe. Consequently, the infrastructure implementation of the bicycle street can be described as subjectively safe. However, a deeper look into the data reveals a more nuanced picture. For example, the lane width is generally described as safe, but this rating significantly decreases when a car is placed in close proximity to the observer. Participants get a sense of what it feels like to be overtaken by a car and that the width of the street may not be sufficient (actually according to German rules it is too narrow so overtaking a cyclist by a car is prohibited). The use of qualitative feedback also enhanced the diagnosticity of the data: for instance, experienced cyclists rated the paved safety strip as significantly less safe than inexperienced cyclists. The reason for this was that experienced cyclists often expressed concerns about loss of control with rigid bikes, narrower tires, and generally increased difficulty when starting at traffic lights. In contrast, inexperienced cyclists only saw starting at traffic lights as critical and rated the element as safe. A similar assessment was made of the curbs: experienced cyclists rated them as a risk of injury, as generally unnecessarily high and angular, and missed lowered curbs next to bicycle parking facilities. Inexperienced cyclists did not express these concerns. This leads to the conclusion that, although the infrastructural implementation is generally perceived as safe, there is potential for improvement. When asked how representative the presentation was, the test subjects responded with very representative and that they had the feeling of being there. N = 17 respondents also said that looking at the isolated road environment elements helped them to reflect on their safety concerns and relate safety concerns to specific road environment elements. To this end, the method of VR evaluation might be an effective tool providing a detailed view of the subjective safety of road environment characteristics, without the need for on-site inspections with users of the infrastructure, but more research is needed here. Interestingly, the evaluations were consistent, showing no differences between participants who actually use the bicycle street and those who do not. This implies that this method for evaluating subjective safety can be conducted independently of the participants' familiarity with the specific infrastructure measure.

6 Conclusions

The presented studies demonstrate consistent evaluation results regarding the subjective safety assessment of the showcased bicycle street. The evaluated bicycle street is perceived to be safer than the average bike-accessible infrastructure in the city area of Chemnitz. Key factors influencing this assessment were identified as the lane width and the restrictions on motorized traffic. These results are not surprising and align with the findings of existing literature. However, to the authors' knowledge, Study II is the first to evaluate the perceived safety of cycling infrastructure using VR and stereoscopic 360° images. The results regarding the general subjective safety obtained were not only consistent with those from Study I, a traditional online questionnaire study, but also provided a focused view of road environment characteristics and their perceived safety. It was shown that depending on the presentation (cars in the immediate vicinity) and cycling experience, there are significant differences in the evaluation of individual infrastructure characteristics in VR. These results are interesting because even during a site visit or on-site survey, it would be difficult (detailed evaluation of a single road environment element) or too risky (close but everyday overtaking maneuvers of motorized traffic) to precisely examine different contexts or environmental influences. Furthermore, the presented method offers a structured and controlled way to evaluate cycling infrastructure realistically under laboratory conditions in a resource-efficient manner. Within 15 minutes, participants could evaluate twelve images or scenarios and complete a follow-up questionnaire. Preparing the study was time-efficient due to a self-programmed app; only the scenarios needed to be identified and the images taken. Moreover, the method is location-independent, easily transportable, and can be intuitively used without technical knowledge thanks to VR headsets with integrated computing units. Assuming further evaluation of the method and its potential, it could be used for citizen participation measures or future infrastructure planning projects to evaluate their subjective safety in a resource-efficient manner after completion and to use the findings for future planning projects. This is a process that is rarely, if ever, carried out in planning offices in Germany and can contribute to increased safety of cycling infrastructure in general.

7 Limitations

Both studies were based on a list of infrastructure characteristics that may not have captured all relevant elements, meaning there could be relevant infrastructure characteristics that the studies did not include. Moreover, the images in the questionnaire and especially in VR may have shown influences (e.g. weather) that were not quantified or collected but could affect the evaluation of perceived safety, even though efforts were made to keep the images comparable across both studies and to exclude disturbing influences. Additionally, the rating scheme in both studies was different, which makes the results only partially comparable. Furthermore, the sample compositions in both studies were different: Study I involved only users of the bicycle street, while Study II also included non-users. Another point is the small sample size in Study II, which could impact the validity and reliability of the data. Moreover, the VR method applied in Study II is not yet fully mature, which could affect the participants' evaluations.

CRediT contribution statement

Marc Schwarzkopf: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft. **André Dettmann:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—review & editing. **Angelika C. Bullinger:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing—review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics statement

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About the authors

Marc Schwarzkopf began working at the chair in the field of product ergonomics after successfully completing his studies in sensory and cognitive psychology and working for Deutsche Telekom in 2020. His research interests are focused on sustainable mobility, particularly the investigation of bicycle safety and the evaluation of urban infrastructure. Additionally, he conducts research in the field of virtual reality and ergonomics, connecting all these areas together.

André Dettmann began working at the chair in the field of product ergonomics after successfully completing his Systems Engineering studies in 2012. André Dettmann primarily focuses on research questions related to driver assistance systems and highly automated driving. Additionally, he is engaged in general topics related to human-machine interaction. He also explores topics related to the overall design of urban mobility and questions concerning mobile work.

Angelika C. Bullinger has been heading the Chair of Occupational Science and Innovation Management at TU Chemnitz since April 2012. She completed her studies at the University of St. Gallen (HSG) and HEC Paris. Following that, she worked as a research assistant at the Technical University of Munich, where she earned her doctorate in 'Innovation and Ontologies'. Her habilitation on the topic of 'IT-based Interactive Innovation' was conducted at the University of Erlangen-Nuremberg and the University of Pennsylvania. She has more than 15 years of experience in acquiring and leading national and European projects, advises industrial companies, and regularly delivers lectures and keynotes on the future of work and workers.