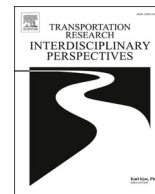


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Virtual reality simulations on Pedestrians' perceived risk in interactions with cyclists

Lama Ayad^{a,*}, Hocine Imine^a, Francesca De Crescenzo^b, Claudio Lantieri^c

^a COSYS-PICS-L, University of Gustave Eiffel, F-77454 Marne-la-Vallée, France

^b Department of Industrial Engineering, University of Bologna, Via Fontanelle 40, 47100 Forlì, Italy

^c Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM), University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy

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ABSTRACT

With the growing popularity of cycling and walking as modes of transportation, pedestrians and cyclists are often considered vulnerable road users due to their lack of safety and the risk of injuries in collisions with other road users or each other. Understanding pedestrian safety perceptions in mixed-use urban environments is essential for developing safer shared infrastructure. This study analyzes pedestrian risk perception in three cyclist–pedestrian interaction scenarios: a blind corner, a crosswalk, and a shared path. Unlike prior studies that focus on pedestrian–vehicle interactions, this study examines perceived risk in cyclist–pedestrian environments using both virtual reality (VR) and matched real-world video conditions. A total of 42 participants experienced all scenarios and provided subjective risk ratings. Results from paired sample t-tests revealed no significant differences in perceived risk between VR and video conditions for all scenarios (p -value > 0.05). However, shared path conditions showed the highest perceived risk, underlining the need for infrastructure designs that reduce user conflicts, such as physical separation. The study extends the validated use of VR to cyclist–pedestrian conflict scenarios within pedestrian safety research and underscores the importance of designing shared facilities that accommodate the needs of all non-motorized users.

Introduction

In European cities, pedestrians and cyclists are essential contributors to sustainable and healthy mobility. Their number has increased in recent years. For example, cycling levels in Paris grew by approximately 60% between 2019 and 2021 (European Commission, 2023). In addition, 65% of people in the European Union reported walking for short trips as their primary mode of transportation in 2023 (Statista Research Department, 2023). However, these road users remain highly vulnerable, particularly when sharing infrastructure with motor vehicles or with each other, as they lack protection against the speed and mass of motorized traffic (European Transport Safety Council, 2022). Vulnerable road users, including pedestrians and cyclists, accounted for approximately 70% of urban road fatalities in the EU (European Commission, 2024). Pedestrians represented 17% of all road traffic fatalities, while cyclists accounted for around 8% in 2022 (European Transport Safety Council, 2022).

While much of the existing research focuses on pedestrian–vehicle collisions, interactions between pedestrians and cyclists are increasingly

recognized as an important safety concern, particularly in shared spaces such as crosswalks and multi-use paths. As cycling infrastructure expands, pedestrian–cyclist interactions are becoming more frequent. Batista and Friedrich (2022) found that 28% of interactions between pedestrians and cyclists in shared environments resulted in potential conflicts, a higher proportion than pedestrian–motor vehicle (22%) or cyclist–motor vehicle (25%) interactions. These findings highlight significant safety implications for pedestrians, especially when cyclists travel at high speeds or behave unpredictably. Although less frequent than motor vehicle collisions, pedestrian–cyclist conflicts can still result in serious injuries due to the lack of physical protection and the close proximity of interactions. Similarly, Mesimäki and Luoma (2021) reported that near-accidents between pedestrians and cyclists occur approximately 50 times more frequently than documented collisions, yet are often unreported. Their study also showed that pedestrians tend to suffer more severe injuries in such interactions, particularly on shared paths where sudden cyclist maneuvers are common. Furthermore, Beitel et al. (2018), using automated video conflict analysis of more than 2,700 pedestrian–cyclist interactions, observed that conflict frequency

* Corresponding author.

E-mail address: lama.ayad@univ-eiffel.fr (L. Ayad).

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increased significantly with pedestrian density, even when crash data did not reflect a corresponding rise. These results demonstrate the limitations of traditional crash statistics and underline the need for alternative approaches, such as perception-based methods, to better understand pedestrian risk in shared environments. Cyclists generally prefer dedicated infrastructure, such as bicycle lanes or separated paths, which they perceive as safer and more comfortable. Fosgerau et al. (2023) suggested that the implementation of fully separated bicycle path networks led to a 60% increase in cycling rates. However, even highly desirable cycling facilities may present risks when pedestrians and cyclists share the same space. This was confirmed by previous experiments using a bicycle simulator, which showed that cyclists felt more vulnerable on bicycle paths shared with pedestrians than on dedicated bicycle lanes, mainly due to concerns about unpredictable pedestrian movements and potential conflicts (Ayad et al., 2024).

Despite the frequent coexistence of pedestrians and cyclists in urban environments, relatively few studies have examined how pedestrians perceive risk in spaces shared with cyclists. This gap is partly explained by the rarity of pedestrian–cyclist collisions and the difficulty of collecting reliable crash data for these events (Beitel et al., 2018). Consequently, alternative methods, such as real-time perception measurements in controlled experimental settings, are required. Virtual reality (VR) has emerged as a powerful research tool, offering immersive experiences that allow the safe evaluation of risk perception. Its applications span multiple fields, including industrial product engineering, education, training, and road safety. VR provides immersive three-dimensional experiences at relatively low cost while minimizing user distraction (Vankov & Jankovszky, 2021). Compared to desktop simulations, large screens, or CAVE systems, head-mounted VR displays enable full immersion, natural head movements, and enhanced spatial awareness, which are critical when evaluating perceived risk during close interactions with cyclists.

VR has been widely used in road safety research to assess simulator sickness, perceived safety, and behavioral responses in urban environments. For instance, Bialkova et al. (2018) used VR to examine the effects of infrastructure characteristics—such as bicycle path width, traffic volume, and environmental greenness—on cyclists' perceptions of safety and enjoyment. Similarly, Schwarzkopf et al. (2024) evaluated perceived safety, comfort, and acceptance of various cycling infrastructures using VR, with participants' assessments closely matching those of infrastructure experts. With respect to pedestrians, VR has been applied to investigate behavioral and perceptual responses under controlled conditions. Iryo-Asano et al. (2018), for example, analyzed pedestrian safety in shared spaces using interactive VR simulations and found that perceived danger was greater for lateral approaches, potentially due to reduced fields of view. Likewise, Kwon et al. (2022) demonstrated how environmental design elements influence perceived crash risk, crossing speed, and decision-making.

Nevertheless, most existing studies focus on pedestrians or cyclists separately, or on interactions between pedestrians and motorized vehicles, rather than on pedestrian–cyclist interactions from the pedestrian's perspective. While Kamalasanan et al. (2022) evaluated the technical stability of mixed reality frameworks for pedestrian–cyclist interactions, their study did not address risk perception or infrastructure design. Instead, it demonstrated how mixed reality can enhance simulation realism by allowing real pedestrians to interact with virtual cyclists in real environments.

As a result, how pedestrians perceive risk in the presence of cyclists, and how this perception varies across different types of shared infrastructure, remains underexplored. This study aims to address this gap by investigating pedestrians' perceived risk during interactions with cyclists in various shared urban environments using VR simulations, complemented by real-world video recordings of comparable scenarios. The study provides a detailed analysis of how different infrastructure types influence perceived risk and whether the presence of cyclists significantly affects pedestrians' risk perception.

In addition to VR simulations, real-world video recordings of the same scenarios are included to validate the ability of VR to reproduce real-world risk perceptions.

This study addresses the following research questions:

- RQ1: How similar are pedestrians' perceived risk levels in VR compared to real-world video recordings of shared infrastructure types?
- RQ2: How do different shared infrastructure types influence the perceived risk levels of pedestrians in the presence of cyclists?

RQ1 evaluates the realism of VR in reproducing pedestrian risk perception, while RQ2 examines how perceived risk varies across infrastructure types due to environmental and behavioral differences.

Methodology

This study evaluates pedestrians' perceived risk in shared urban facilities using immersive virtual reality (VR) and real-world video recordings. The objectives are to compare perceived risk across three shared infrastructure types and to assess the similarity of risk perception between immersive VR scenarios and real-world video representations.

In addition, results from a previous bicycle simulator study (Ayad et al., 2024) are referenced in the final stage of the analysis to compare pedestrians' risk perceptions with cyclists' perceptions in a common shared scenario.

The following sections describe in detail the development of the VR simulations, the recording of real-world videos, the experimental protocol, and the analytical framework used to evaluate pedestrian risk perception and the reliability of VR.

VR simulation system overview and design

A Meta Quest headset was used for the experiment. The device provides a high-resolution display of 3664×1920 pixels (773 PPI), a refresh rate of up to 120 Hz, and an approximate field of view (FOV) of 110° , which is sufficient to offer a natural and immersive pedestrian perspective in dynamic environments. The Meta Quest was selected because it operates independently without requiring a PC connection (Meta, n.d.) and is known for its ease of setup, practicality, and high graphical fidelity. This configuration eliminated spatial restrictions caused by cables, allowing participants to move freely while remaining fully immersed in the virtual environment. In addition, the system facilitated the definition of safe VR boundaries within the experimental space.

Unity was used to develop and simulate the virtual environments, including the creation of virtual cyclists. This software was chosen for its compatibility with the Meta Quest headset and its capacity to generate responsive and near-realistic environments. Unity also enabled the integration of assets created in Blender, which was used to develop textures and three-dimensional models for buildings, road furniture (e.g., markings, surfaces, trees, and signage), and parked vehicles. The process involved designing, optimizing, and assembling the virtual scenarios using Blender and Unity before deploying them to the Meta Quest headset.

VR scenarios development and optimization

A local road in Bologna was selected as the study site because it includes critical intersections, shared pedestrian–cyclist paths, and crosswalks with bicycle lanes. The VR environment was developed to replicate the area surrounding Piazza di Via Pasubio, based on detailed in-field measurements and on-site observations.

The VR experiment included three infrastructure types in interaction with cyclists: (1) shared path (SP), (2) crosswalk (CW), and (3) blind corner (BC):

- Scenario 1 – shared path (SP): This scenario includes a pedestrian lane adjacent to a cyclist path, with an obstacle present on the pedestrian lane. As shown in Fig. 1 (left), participants initially encountered a construction zone measuring 0.6 m in width and 2.4 m in length, which required them to step onto the cyclist path to continue walking. Virtual cyclists approached from both directions along the cyclist path.
- Scenario 2 – crosswalk (CW): Participants crossed a zebra crosswalk measuring 4 m in width and 10 m in length while virtual cyclists approached from a distance of 15 m (Fig. 1, middle).
- Scenario 3 – blind corner (BC): Participants approached a corner with limited visibility. Once they reached within 1.5 m of the corner, a virtual cyclist appeared and traveled along the path. The corner was modeled with a 90° turn and a 1.2 m-wide sidewalk (Fig. 1, right).

These three scenarios were selected because they represent common pedestrian–cyclist conflict points found in European cities and are consistent with infrastructure types highlighted in pedestrian safety research (González-Gómez & Castro, 2019; Gruden et al., 2021). The virtual scenarios included realistic roadway geometry, environmental elements (e.g., construction zones, signage, surface markings), and cyclist behaviors derived from detailed site measurements and previous observational studies. These design choices ensured a high level of situational validity and allowed the VR scenarios to faithfully represent real-world pedestrian–cyclist interactions.

Participants were able to use the full length of the laboratory room (12 m) and a width (5 m) to walk freely during the VR experiment. The room was unobstructed and the VR environment was bounded within this space. When participants approached the limit of the room, a virtual boundary within the VR appeared, warning them that they were nearing the edge of the area and should not proceed outside of it.

Participants and cyclists' movement directions are shown using red and blue arrows, respectively, while the critical interaction point is indicated by a red "X."

Virtual cyclists were created in Unity by integrating 3D modeling, rigging, animation, and interactive scripting to simulate natural pedaling, steering, and body movements (Fig. 2). The average speed was set to 12 km/h in the virtual reality, similar to the speed of real cyclists in the bicycle simulator (Ayad et al., 2024). Cyclist speed and lateral movement were calibrated based on typical urban cyclist behavior observed during field measurements.

Given the complexity and size of the VR environment, performance optimizations were applied to ensure smooth rendering on the Meta

Quest headset. These optimizations enhanced responsiveness and contributed to a more immersive experimental experience (Unity Technologies, 2021). Fig. 3 presents a top-down view of the virtual urban environment, showing all three scenarios: shared path (SP), crosswalk (CW), and blind corner (BC). Scenario boundaries are indicated by color-coded boxes: red for SP, green for CW, and orange for BC. Each scenario was experienced independently with full 360° visibility.

Real road videos design

Real-world videos were recorded at the same location in Bologna to measure the perceived level of risks of participants under real conditions. The videos had replicated exactly the same scenarios developed in Unity in terms of cyclist speed, trajectory, and interaction distances. The purpose of this part was to determine whether real road conditions influenced participants' risk perceptions similarly to those observed in VR scenarios.

The recordings were recorded using a handheld smartphone camera held at eye level to replicate a pedestrian's viewpoint. This method provided a realistic visual perspective of the environment and pedestrian–cyclist interactions.

Participants

Participants were randomly recruited through departmental mailing lists and central campus affiliations at the University of Bologna. Eligibility criteria included: (1) being 18 years of age or older and (2) not wearing glasses that would interfere with the VR headset. Participation was entirely voluntary, and all participants agreed to take part in the study. A written consent form and a data protection form before the experiment were provided to the participants, and the procedure was approved by the Institutional Ethic Board of Bologna University. Forty-two volunteers participated in this study in total.

VR experiment protocol

The experiment consisted of six stages, as outlined in Fig. 4, undertaken sequentially by each participant to assess risk perception across three pedestrian–cyclist interaction scenarios in both virtual and real-world environments. After being welcomed and briefed, participants completed a consent form and a pre-experiment questionnaire collecting demographic information, walking frequency, collision history, and prior VR experience. They then entered a familiarization environment in VR to become accustomed to the headset and navigation interface.

Subsequently, participants experienced three VR scenarios

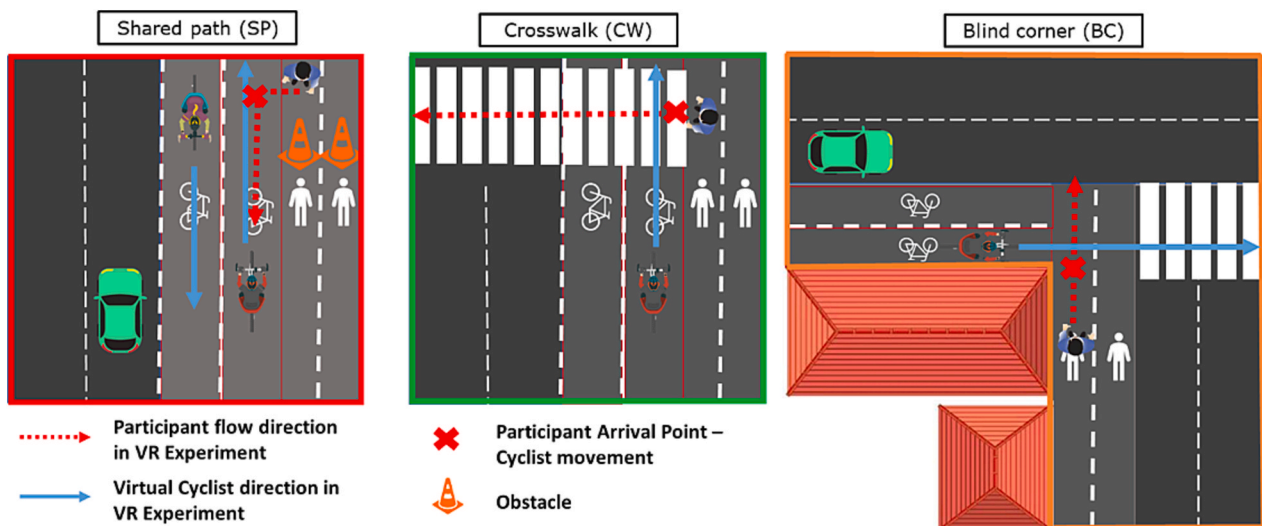


Fig. 1. Schematic illustration of the experiments for SP, CW, BC.

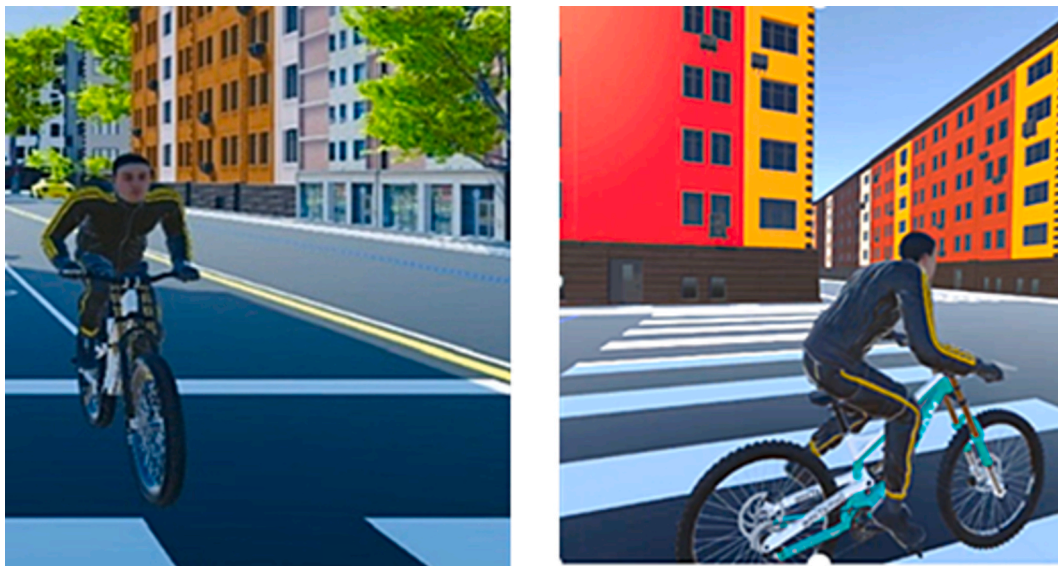


Fig. 2. Virtual cyclist in scenarios.

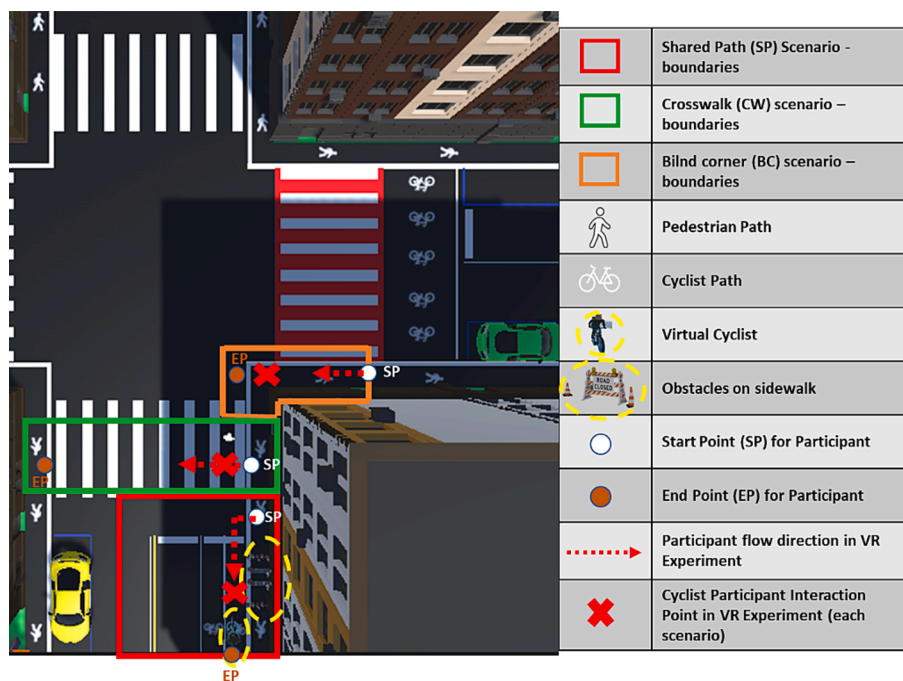


Fig. 3. Top-down view of the virtual environment showing three scenarios: shared path (red), crosswalk (green), and blind corner (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

simulating different pedestrian–cyclist interactions: Shared Path (SP), Crosswalk (CW), and Blind Corner (BC). The scenario order was randomized to minimize fatigue and learning effects. During each scenario, participants moved naturally through the environment, following directional arrows when provided, while the experimenter monitored the VR display mirrored on a laptop. A virtual boundary system alerted them when nearing the limits of the physical space.

After completing the VR scenarios, participants rated their perceived risk for each one using a post-VR questionnaire. They then viewed real-world video recordings of the same three scenarios captured from an equivalent pedestrian viewpoint at the same location. A second questionnaire was administered to compare perceived risk in the real-world conditions. This workflow allowed for direct comparison of individuals’ perceived risk between immersive VR and real-world environments.

Measures

Two metrics were measured in this experiment: risk perception and VR experience evaluation. Risk perception reflected the ability of participants to evaluate the characteristics and severity of specific risks.

Risk perceptions

Risk perception was assessed via a 5-point Likert scale: 1 (strongly disagree) to 5 (strongly agree). It was quantified by worry and concern adapted from (Rundmo & Iversen, 2004), the potential impact of road users on their risk level adapted from (Kummeneje, 2020), and perceived risk and danger adapted from (Machin & Sankey, 2008). A 5-point Likert scale was chosen as it offered sensitivity while being easy for participants to interpret during immersive tasks.

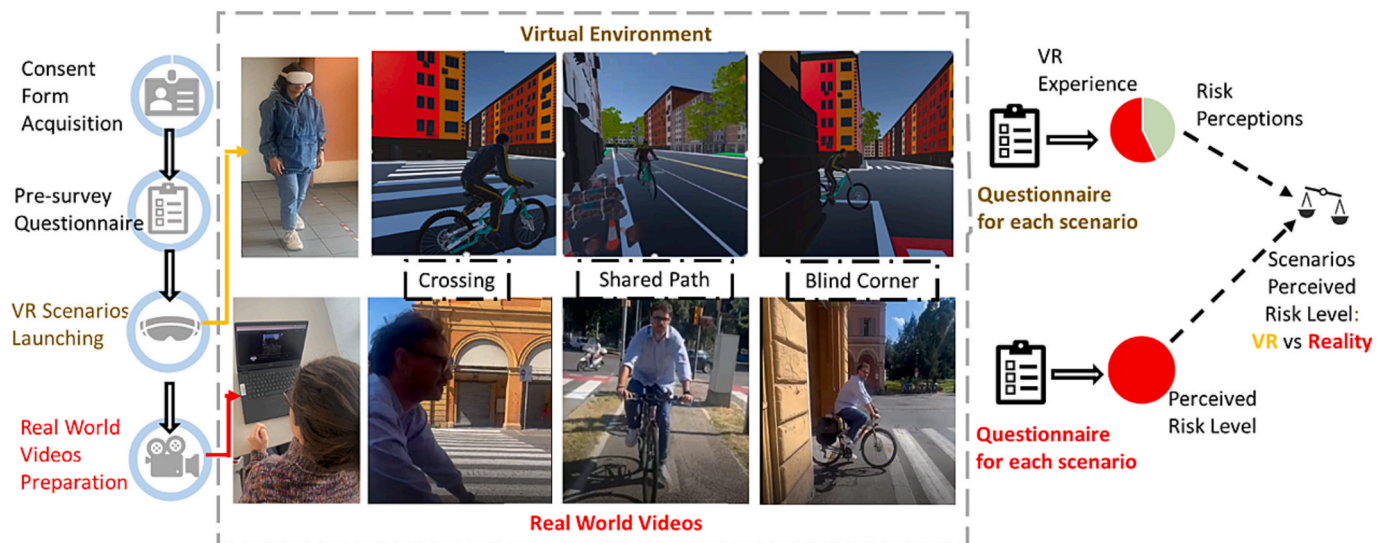


Fig. 4. Experimental Workflow: Virtual (top row) and real-world (bottom row) environments for the three scenarios.

For each scenario, participants rated:

- Perceived risk level in the scenario “While walking in this road, I found the level of risk very high”.
- Fear of collision with cyclists: “In this scenario, I was afraid of being collided with by cyclists”.
- Perceived impact of cyclist presence on risk: “To what extent does the presence of cyclists affect your perceived risk while walking in the scenarios”.

Evaluation of the VR experience

Different factors were assessed to evaluate the efficacy of using VR as a tool for understanding risk perceptions and for studying transportation safety:

- Simulator sickness: Selected items from the Simulator Sickness Questionnaire (SSQ) were used to assess symptoms such as nausea and discomfort (Kennedy et al., 1993). Other symptoms (e.g., oculomotor strain, disorientation) were excluded in this study since they have already been extensively analyzed in prior studies, which confirmed that the severity of simulator sickness increases with increased exposure time (Dużmańska et al., 2018).
- Image quality: The quality of the picture was high.
- Level of immersion: I felt immersed in the experience.
- Level of realism: The VR scenario felt realistic, like walking on real street.

Participants rated the other aspects such as image quality, level of immersion, level of realism using 5-point Likert scale: 1 (strongly disagree) to 5 (strongly agree).

Data framework for analysis

Statistical analyses were conducted using R software. The following tests were used:

- VR vs. real-world comparisons: A paired *t*-test was conducted for each scenario to compare perceived risk ratings between VR and real-world videos for each. As discussed previously, the *t*-test was chosen because it is appropriate for comparing the means of two related samples in order to assess whether there is a statistically significant difference between the two tools scenario (Ross & Willson, 2017).

- Scenario risk comparison: A Friedman test was used to compare the perceived risk ratings across the three scenarios. This non-parametric test was chosen due to the repeated measures design of the study and the violation of ANOVA assumptions. Post-hoc pairwise comparisons were followed using the Wilcoxon signed-rank tests to identify the riskiest scenario (Kim, 2014).
- Descriptive statistics: Means, standard deviations, and the percentage of participants were reported for all VR experience indicators.
- Pedestrian vs. cyclist comparison: A Mann-Whitney *U* test was performed to compare pedestrian’s VR perceived risk ratings with cyclists’ simulator data for a common shared scenario. This non-parametric test was chosen for its suitability in comparing medians between two independent groups with non-normally distributed data (MacFarland & Yates, 2016).

Results

Participants overview

Demographic characteristics, walking habits, and collision history were collected through a pre-survey questionnaire. Table 1 summarizes the sociodemographic profile of the 42 participants, categorized by age distribution, walking frequency, previous collisions, and familiarity with virtual reality (VR). The sample consisted of 55% males and 45% females, with 43% aged between 26 and 49 years. Nearly half (48%) reported walking as their primary mode of transportation, and 21% walked more frequently than they used other transport modes.

In terms of prior exposure, 50% of participants had used VR before, and 95% reported no symptoms of cybersickness during previous VR experiences. However, their VR use was primarily for leisure rather than for safety-related simulations such as the one conducted in this study.

Regarding collision history, 38% of participants reported involvement in accidents within the past six months, with 83% of these incidents occurring during the day. Bicycle-related collisions accounted for 58% of reported cases, followed by vehicle (26%) and motorcycle collisions (16%). Most collisions were attributed to road user behavior (70%), with infrastructure issues and excessive speeds by others contributing to 16% and 14% of incidents, respectively. Although 61% reported no injuries, 33% sustained minor injuries.

Scenarios’ risk perceptions

The number of items, mean scores, standard deviations (SD), and

Table 1
Sociodemographic Characteristics and VR Experience of Participants.

	Males (N = 23)		Females (N = 19)		Total (N = 42)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Age						
18–25	10	43%	13	68%	23	55%
26–49	12	52%	6	32%	18	43%
50–64	1	4%	0	–	1	2%
Walking frequency as a main mode of transportation						
Always	13	57%	7	37%	20	48%
More often	3	13%	6	32%	9	21%
Frequently	5	22%	2	11%	7	17%
Sometimes	2	9%	4	21%	6	14%
Rarely	–	–	–	–	0	–
Previous collisions occurrence with other road users in the last 6 months						
Not involved	10	43%	16	84%	26	62%
Involved	13	57%	3	16%	16	38%
VR Use Previous Experience						
No Use	10	43%	11	58%	21	50%
Use	13	57%	8	42%	21	50%
Previous cybersickness using VR						
Not Experienced	13	100%	7	88%	20	95%
Experienced	–	–	1	12%	1	5%

This diverse sample, varying in age, gender, walking habits, and prior exposure to cyclists, reflects a typical urban pedestrian population. It also supports the relevance of the study’s findings to real-world pedestrian–cyclist interactions.

internal consistency for risk perception across the three scenarios: shared path (SP), crosswalk (CW), and blind corner (BC) are presented in Table 2. The mean risk perception scores were similar for the blind corner (M = 3.65) and shared path (M = 3.60) scenarios, and both were higher than the mean score for the crosswalk scenario (M = 2.50).

To assess the reliability of the risk perception scale used in the virtual reality (VR) experiment, Cronbach’s alpha was calculated. Cronbach’s alpha is a widely used statistical measure that evaluates the internal consistency of a set of items within a scale, that is, how closely related the items are as a group (Bonett & Wright, 2015). A higher Cronbach’s alpha value indicates that the items are closely related and consistently reflect the same underlying construct across participants’ responses.

Cronbach’s alpha was calculated separately for each scenario to evaluate the consistency of the risk perception scale. The results were as follows: shared path = 0.52, crosswalk = 0.70, and blind corner = 0.67. Values above 0.70 are generally considered acceptable, values between 0.60 and 0.70 are considered questionable but usable, and values below 0.60 indicate low reliability. The blind corner and crosswalk scenarios yielded acceptable or near-acceptable reliability. However, the shared path scenario showed lower reliability, which may indicate that participants had more varied opinions about the level of risk in that situation.

The Friedman test was used to verify whether there were significant differences in perceived risk across the scenarios. This test was selected due to violations of ANOVA assumptions, including normality and homogeneity of variance. This test indicated a significant difference in overall risk perception across the three scenarios ($\chi^2 = 13.779$, $df = 2$, p -

value = 0.001).

Post-hoc pairwise comparisons were conducted using the Wilcoxon signed-rank test to identify which scenario pairs differed significantly in perceived risk. The results showed a statistically significant difference between the blind corner and crosswalk scenarios (p -value < 0.001), with participants perceiving the blind corner as significantly riskier. No statistically significant differences were found between shared path and blind corner scenarios (p -value = 0.14), or between shared path and crosswalk scenarios (p -value = 0.16). Therefore, based on the combined risk perception measures, the blind corner scenario was considered the highest-risk environment among the three.

In the following sections, each risk perception measure, such as perceived risk level, fear of collision, and perceived impact level, is analyzed separately. For perceived risk level, comparisons between VR experiment responses and recorded video responses are also discussed in detail.

Perceived risk and cyclist influence in virtual scenarios

Participants evaluated the perceived risk level of each VR scenario by indicating whether walking in the scenario posed a very high risk.

The blind corner scenario received the highest perceived risk rating (M = 3.76, SD = 1.12), with 62% of participants expressing high concern (see Fig. 5). The shared path scenario also received elevated ratings (M = 3.31, SD = 1.16), while the crosswalk scenario was rated lowest (M = 2.69, SD = 1.45). This pattern is consistent with the distributions shown in Figs. 5 and 6. Fig. 5 presents the percentage of risk ratings for each scenario, while Fig. 6 shows the distribution of perceived risk scores

Table 2
Number of measures, mean scores and Cronbach’s alpha for risk perception.

Measures	Number of Items	Mean (range 1–5)			SD			Cronbach’s alpha		
		SP	CW	BC	SP	CW	BC	SP	CW	BC
		Perceived risk level	3	3.6	2.5	3.65	0.87	1.02	0.8	0.52
Fear of collision										
Perceived impact level										

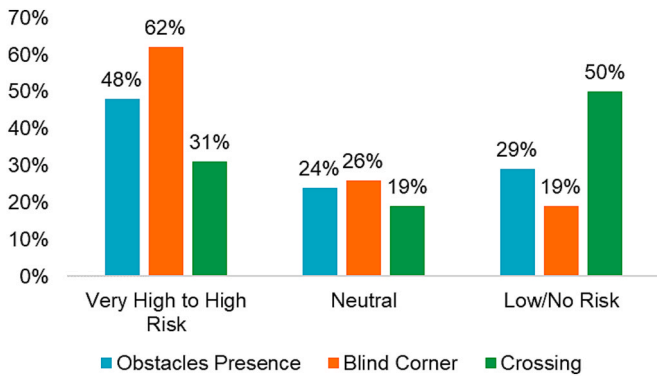


Fig. 5. Participants rating percentage for each VR scenario.

across all three VR scenarios. Responses for the blind corner scenario are right-shifted toward higher risk levels, whereas crosswalk ratings are largely clustered in the lower range, confirming the statistical results.

Furthermore, participants were asked about the impact of cyclists on their perceived risk. As shown in Fig. 7, 36% of participants reported that cyclists had a strong impact on their perceived risk on shared paths, while 24% indicated a moderate impact. For the blind corner scenario, 33% reported a moderate impact, and 17% reported a strong impact. In

contrast, 83% of participants indicated that cyclists had little to no impact on their perceived risk in crosswalk scenarios. Therefore, cyclists' presence was perceived to have the greatest influence on risk in shared path scenarios, a moderate influence in blind corner scenarios, and minimal influence in crosswalk scenarios.

Regarding fear of collisions, 64% of participants expressed high levels of fear regarding collisions with cyclists on a shared path, while 60% of participants reported being very strongly to strongly afraid of bicycle collisions when walking in a blind corner (refer to Fig. 8). On the other hand, 36% of participants reported being extremely afraid of collisions when crossing the street, whereas 43% reported feeling extremely unafraid. Therefore, most participants reported fear of collisions with cyclists in shared path and blind corner scenarios. As a result, these situations are perceived as more dangerous than crosswalks.

Scenarios' perceived risk level in VR versus real-world videos

The question of perceived levels of risk, using the same scale and structure, was asked of participants when they viewed the real-world videos. The perceived risk results from the VR and real-world environments are shown in Fig. 9. The results show that risk ratings in VR and real-world videos were highly similar across scenarios: blind corner ($Mean_{VR} = 3.76, Mean_{Video} = 3.67$), shared path ($Mean_{VR} = 3.31, Mean_{Video} = 3.17$), and crosswalk ($Mean_{VR} = 2.69, Mean_{Video} = 2.95$). This indicates that VR can fairly reproduce aspects of the real-world

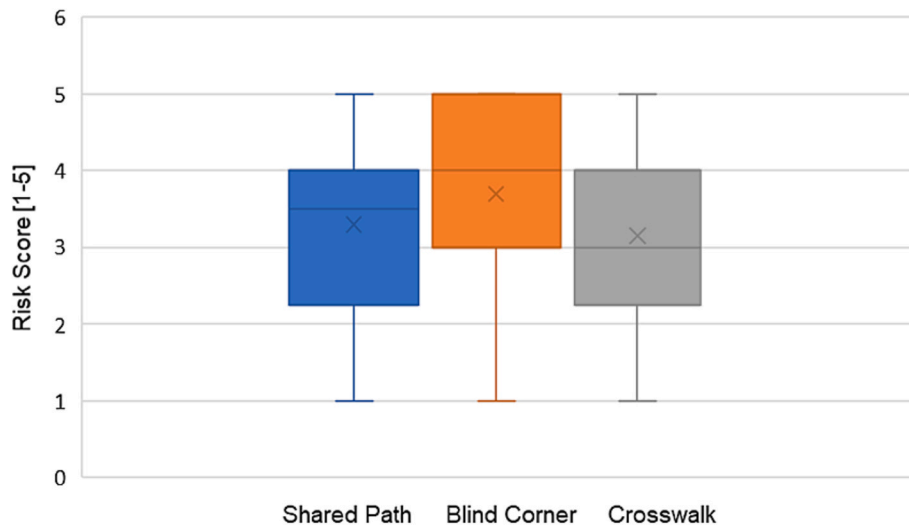


Fig. 6. Perceived risk distribution across VR scenarios.

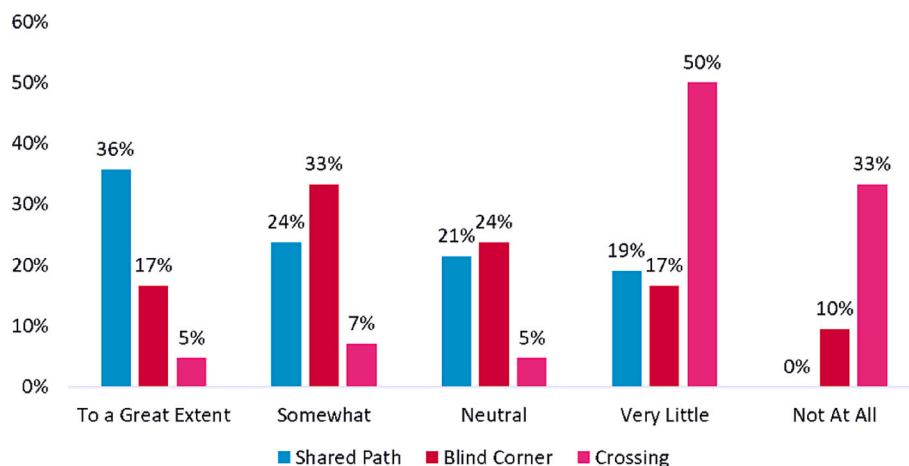


Fig. 7. Percentage distribution of perceived impact of cyclists for each VR scenario.

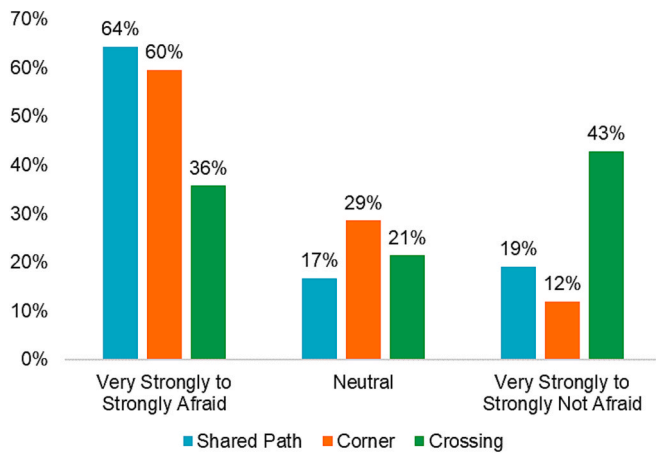


Fig. 8. Percentage distribution of fear levels regarding cyclist collisions by scenario.

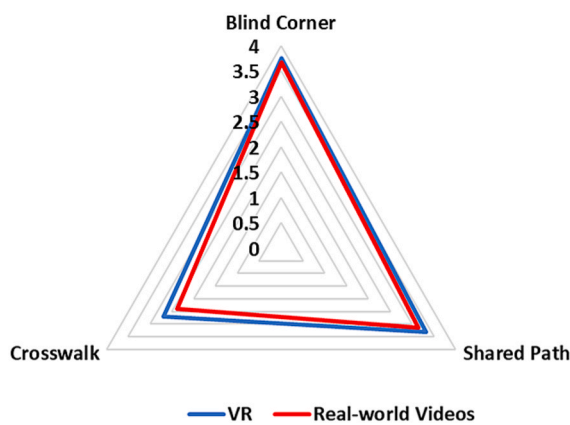


Fig. 9. Mean perceived risk levels in VR and reality for different scenarios.

experience, particularly across different scenario conditions. This was confirmed by paired t-tests showing no statistically significant differences across scenarios.

Three paired t-tests were conducted to compare perceived risk ratings between VR and real-world video conditions for each of the three pedestrian–cyclist interaction scenarios (see Table 3). Under the null hypothesis, no significant difference was expected between the two conditions.

The results showed no statistically significant differences in perceived risk for the blind corner scenario ($t(41) = 0.36, p = 0.717$) or the shared path scenario ($t(41) = 0.90, p = 0.372$). For the crosswalk scenario, the difference was marginally non-significant, with slightly lower perceived risk in VR ($t(41) = -1.92, p = 0.062$). Overall, these findings indicate that immersive VR replicates real-world risk perception accurately, without amplifying perceived risk in any of the tested environments.

Table 3
Comparison of perceived risk ratings between VR and real-world video conditions across scenarios.

Scenario	Mean (VR)	Mean (Video)	Mean Diff	t(41)	p-value	95% CI (Diff)
Blind Corner	3.76	3.67	0.1	0.364	0.717	[-0.43, 0.62]
Crosswalk	2.69	2.95	-0.26	-1.918	0.062	[-0.54, 0.01]
Shared Path	3.31	3.17	0.14	0.903	0.372	[-0.18, 0.46]

These results confirm the validity of VR for assessing pedestrian–cyclist interactions, particularly in situations that are difficult or unsafe to study in real environments. Higher perceived risk ratings for blind corners emphasize the importance of visibility; improving sightlines and removing obstructions could reduce perceived danger by prioritizing measures such as enhanced corner visibility and warning markings to reduce uncertainty in such locations. Shared paths should also benefit from complete separate paths and additional measures, such as cyclist speed moderation to improve pedestrian comfort and safety.

Participants feedback on the VR environment

Most participants gave high ratings (4 or 5) in all aspects evaluated (picture quality, immersion, realism, ease of use, nausea, discomfort, and overall satisfaction), as shown in Fig. 10.

For picture quality, 86% of participants rated it as 4 or 5, with a mean score of 4.36 (SD = 0.73). Furthermore, 79% of participants reported feeling highly immersed in the VR scenarios, with a mean score of 4.33 (SD = 0.82). In addition, 85% of participants reported their walking experience in VR as realistic (ratings of 4 or 5; Mean = 4.24, SD = 0.85). Moreover, 88% of participants found the VR system simple and easy to use (Mean = 4.52, SD = 0.77), and 93% highly appreciated the overall VR experience (Mean = 4.62, SD = 0.62).

Regarding VR simulator sickness (refer to Fig. 10, bottom), 74% of participants reported no physical comfort, while 17% experienced slight discomfort (Mean = 1.48, SD = 0.92). Furthermore, 70% of participants reported no nausea, and 12% reported slight nausea (Mean = 1.4, SD = 0.7). Although simulator sickness remains a challenge in VR research, factors such as short exposure durations, high-quality hardware, and accurate motion tracking probably contributed to the low levels of nausea and discomfort reported by participants.

These results indicate that the VR experiment provided a practical and safe tool for evaluating different infrastructure designs in terms of road safety.

Shared path comparison between cyclists' perspectives and pedestrian perspectives

To better understand how different vulnerable road users perceive risk in shared facilities, this study replicated one scenario from a previous bicycle simulator experiment (Ayad et al., 2024) involving a shared path used by both cyclists and pedestrians. In that study, cyclists rode through a shared pedestrian–cyclist path and evaluated their perceived level of risk. To enable direct comparison, the same scenario was reconstructed in VR from the perspective of pedestrians interacting with virtual cyclists.

Findings from the previous study showed that 33% of cyclists rated the shared path as presenting high or very high risk, reflecting concerns related to sudden pedestrian movements and limited lateral clearance. In the present VR experiment, 48% of pedestrians rated the same path as high or very high risk, indicating a slightly higher level of perceived vulnerability (Fig. 11). Despite this difference, statistical analysis using the Mann–Whitney *U* test revealed that the distributions of perceived risk were not significantly different ($p = 0.11$), indicating that both road user groups share similar safety concerns in shared-path environments.

Discussion

The first objective of this study was to validate whether pedestrian risk perceptions in immersive virtual reality (VR) align with those observed in real-world videos during interactions with cyclists. The results show that VR produced perceived risk levels similar to those observed in real-world video recordings across all three scenarios, with no significant differences identified using paired t-tests (all p-values > 0.05). This indicates that VR did not amplify perceived risk and that subjective perceptions remained consistent across both tools. For

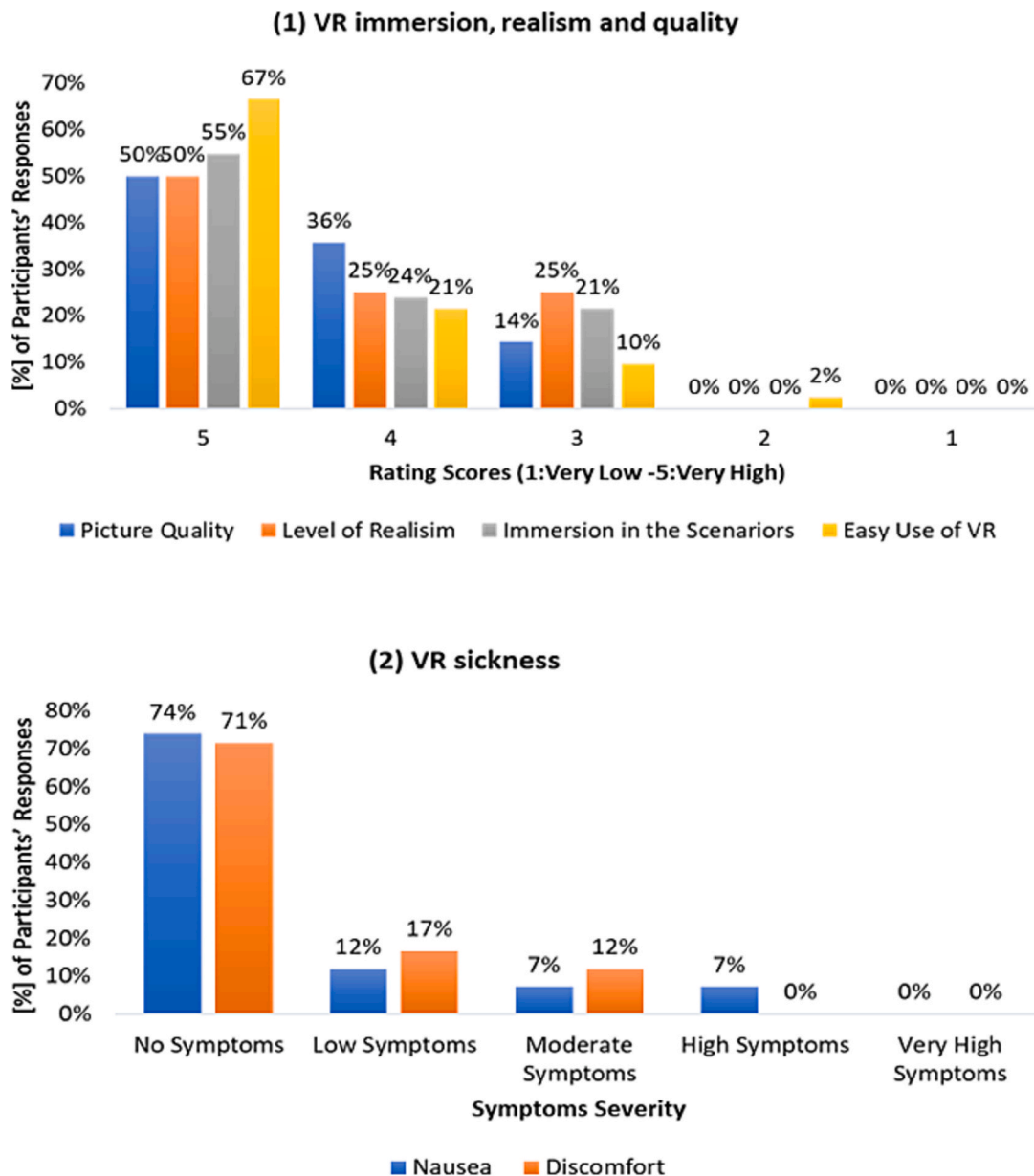


Fig. 10. VR experiment evaluation by participants.

instance, in the blind corner scenario, mean perceived risk was 3.76 (SD = 1.12) in VR and 3.67 (SD = 1.06) in video recordings. These findings demonstrate that the VR environments were accurately designed to reflect real-world conditions. These results align with a previous study by Bhagavathula et al. (2018), who found no significant differences in pedestrian risk perception, safety assessment, or crossing intention between immersive VR and real-world environments. Together with (Angulo et al., 2023), this supports the validity of VR for studying pedestrian behavior, and the present work extends this validation to pedestrian-cyclist interactions. Similarly, Angulo et al. (2023) found that participants perceived simulated environments as comparable to real urban roads. Participants in the present study also reported high levels of realism (M = 4.24/5) and immersion (M = 4.33/5) during VR sessions, further supporting the use of VR as a behaviorally valid research tool. This is consistent with findings from Angulo et al. (2023), who demonstrated that high VR fidelity improves presence, reduces simulator sickness, and enables immersive simulations to replicate real-world pedestrian behavior while remaining engaging for users.

In terms of scenario ratings, perceived risk varied significantly across

infrastructure types (Friedman $\chi^2 = 13.779$, $p = 0.001$). The blind corner scenario exhibited the highest perceived risk (M = 3.76, SD = 1.12), with 62% of participants rating it as “high” or “very high” risk. Participants attributed this increased risk to limited sight distance and the sudden appearance of cyclists, which aligns with findings by Kwon et al. (2022), who reported that reduced visibility and geometric constraints significantly elevate perceived risk and crash potential for pedestrians. These results confirm that even in the absence of observed conflicts, geometric features such as blind corners can strongly influence perceived danger.

The shared path scenario, with a mean rating of 3.31, was also perceived as risky, although to a lesser extent than the blind corner scenario. This scenario involved a temporary pedestrian obstruction that forced users into the cyclist space, increasing the likelihood of near-collision events. Previous studies have shown that shared spaces lacking physical separation between different road users (Argota Sánchez-Vaquero et al., 2024) may increase collision risk or generate anxiety and discomfort (Moody & Melia, 2014). Shared environments have been identified as challenging for pedestrians, as noted by Gkekakos et al.

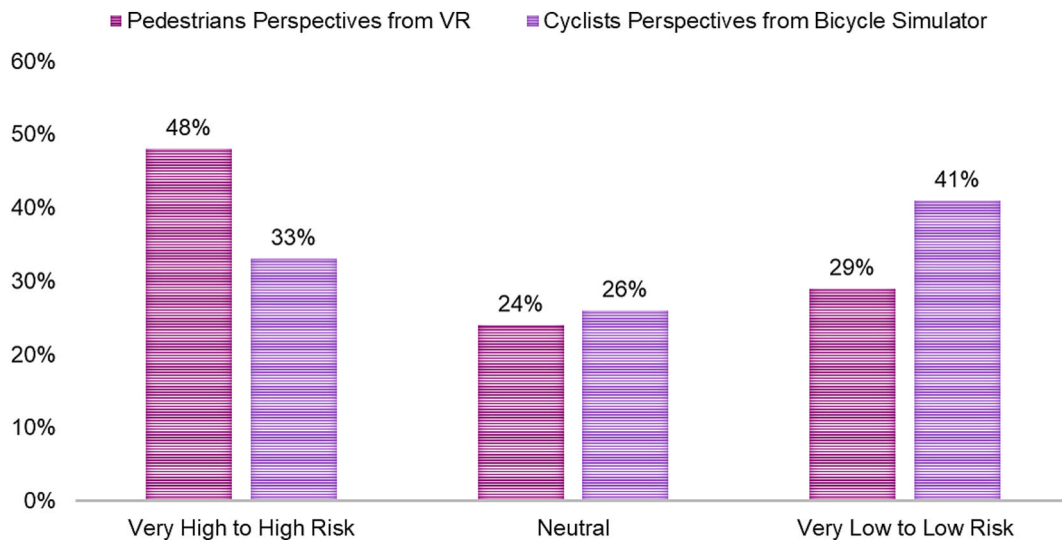


Fig. 11. Comparison of perceived risk levels of shared paths by cyclists and pedestrians.

(2020), since even non-injury incidents can negatively affect perceived safety and comfort, reinforcing concerns regarding the design of high-volume non-motorized shared facilities.

When comparing pedestrian perceptions with results from a previous cyclist study using a bicycle simulator (Ayad et al., 2024), pedestrians rated the shared path as riskier ($M_{ped} = 3.31$ vs $M_{cyl} = 2.87$), although this difference was not statistically significant ($p > 0.05$). Both user groups expressed a preference for dedicated infrastructure, supporting design recommendations that promote the separation of vulnerable road users. These findings emphasize the importance of incorporating both pedestrian and cyclist perspectives in the design of shared mobility environments, as mismatches in perceived safety may lead to discomfort or behavioral adaptations that could reduce overall safety.

Finally, the VR scenarios resulted in minimal simulator sickness, with 95% of participants reporting no discomfort during the experiment. This supports the suitability of the Meta Quest headset and the Unity-based environment for pedestrian behavior research and is consistent with previous studies (Duzmańska et al., 2018; Saredakis et al., 2020), which indicate that appropriate hardware configurations and scenario design can effectively minimize simulator sickness in urban VR simulations.

In summary, VR proved to be a promising tool for studying pedestrian behavior in environments shared with cyclists. Its ability to mimic real-world perception, combined with flexibility in scenario design, suggests strong potential for application in infrastructure evaluation and pedestrian safety research. Future work should focus on expanding the variety of contexts and integrating objective behavioral measures such as walking speed and avoidance distance.

Conclusions

In scenarios that are dangerous or difficult to study in real life, virtual reality has proven to be an effective tool for evaluating the risks of different infrastructure types and understanding pedestrian behavior. This study confirmed that VR can reproduce realistic conditions with high fidelity, as indicated by the comparable risk perceptions observed between VR simulations and real-world recordings. VR therefore provides a safe, controlled, and cost-efficient environment for examining subjective perceptions of risk in complex interactions that cannot easily be analyzed using traditional methods.

This research specifically addressed cyclist–pedestrian interactions, a type of conflict that is rarely examined despite the increasing number of cyclist-related injuries reported in European statistics. Traditional

survey-based approaches cannot capture real-time perceptions for certain scenarios. In contrast, the immersive VR scenarios developed in this study allowed participants to safely experience shared paths, blind corners, and obstructed sections, enabling the analysis of pedestrian discomfort and perceived collision risk.

The results showed that pedestrians tend to perceive higher levels of risk when sharing space with cyclists, particularly in locations where sightlines are limited. These findings highlight the importance of designing shared facilities with attention to visibility, separation, and speed management to improve both perceived and actual safety.

Although the study offers valuable contributions, several limitations should be acknowledged. The sample size of 42 participants, while consistent with recent VR studies on pedestrian behavior (typically including between 30 and 50 participants), remains limited. However, the within-subject design of the experiment increases the statistical power of the analysis. Furthermore, while the virtual environment allowed pedestrians to observe approaching cyclists, real-world interpersonal cues, such as eye contact and subtle negotiation behaviors, could not be replicated. Perceived risk was also measured subjectively; nevertheless, the questionnaire demonstrated acceptable internal consistency, supporting the reliability of participants' responses.

Despite these limitations, the experiment provides a solid foundation for future behavioral studies. Expanding the number and diversity of participants, integrating additional infrastructure variations, and incorporating objective measures, such as walking speed, gaze behavior, reaction times, or crossing decisions, would allow for a more detailed understanding of pedestrian–cyclist dynamics. Based on the present findings, shared spaces without physical separation, particularly blind corners or obstructed paths, should be prioritized in urban design interventions. Enhancing sightlines, improving lane separation, and implementing cyclist speed-reduction strategies may increase pedestrian comfort and safety in these increasingly common environments.

CRedit authorship contribution statement

Lama Ayad: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Conceptualization. **Hocine Imine:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Francesca De Crescenzo:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudio Lantieri:** Writing – review & editing, Validation, Supervision, Methodology, Formal

analysis, Data curation, Conceptualization.

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Declaration of competing interest

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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Institutional review board statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of University of Bologna (protocol code 0156400 and date of approval 05/06/2024).

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Declaration of the Use of AI

The authors declare that no artificial intelligence (AI) or AI-assisted technologies were used in the preparation of this manuscript.

Data availability

Data will be made available on request.

The data supporting the study are not publicly available due to privacy restrictions. The sharing of data is restricted to ensure the confidentiality and privacy of participants by ethical guidelines and institutional policies. However, additional details may be available from the corresponding author (L.A.; lama.ayad@univ-eiffel.fr) upon request.

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