

Article

Risk Perception and Cycling Behaviour: The Role of Pro-Environmental Attitudes and Experience in Urban Sustainable Mobility

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Abstract

Cycling is a key component of sustainable urban mobility, yet cycling behaviours are influenced not only by infrastructure but also by psychological factors, particularly risk perception. This study examined how risk perception, pro-environmental attitudes, and cycling experience relate to cyclists' behaviours in urban contexts. One hundred Italian cyclists completed questionnaires assessing cycling behaviours, environmental attitudes, perceived urban environment characteristics, and hazard perception. Bayesian regression analyses showed that pro-environmental attitudes were associated with safer cycling behaviours, while cycling frequency acted as a protective factor against violations. In contrast, risk perception did not significantly predict cycling errors. The findings suggest that violations and errors may rely on different psychological mechanisms, with violations linked to deliberative processes and errors more strongly associated with automatic cognitive and attentional processes. Overall, the study highlights the need for integrated interventions addressing not only risk awareness, but also environmental design, attentional demands, and motivational factors related to sustainability and social responsibility.

Keywords: risk perception; cycling behaviour; pro-environmental attitudes; sustainable urban mobility

1. Introduction

The decision to use the bicycle as a means of transportation is not determined solely on infrastructural or environmental factors; rather, it is strongly influenced by cognitive and perceptual processes. Among these, risk perception plays a central role in shaping cyclists' behaviour, affecting both their riding practices and the decision to adopt cycling as a transport mode. Consequently, understanding how risk perception is formed and how it influences cyclists' choices is essential for developing effective strategies to promote increased cycling uptake.

1.1. Risk Perception—Objective vs. Subjective Assessment

Risk has been defined as the possibility of injury to a road user caused by objective physical or bodily factors. However, as highlighted by Zhao et al., risk perception does not represent a direct reflection of objective danger; rather, it is a subjective and cognitively mediated evaluation shaped by individual experiences, attitudes, and situational cues [1]. This



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distinction between objective risk and perceived risk is crucial, as behavioural responses are primarily driven by perception rather than by measurable levels of danger. About the relationship between cyclists' traffic safety and risk perception, Zhao et al. (2020) stated that "[...] Whether traffic conflict occurred is determined to be largely affected by cyclists' risk perception. As the sensitivity of risk perception decreases, traffic conflict becomes increasingly likely" (p. 3) [1].

Another influential framework used in the literature to assess risk perception is the "Psychometric Paradigm" developed by Slovic, Fischhoff, and Lichtenstein [2]. This paradigm represents a foundational research framework used to understand public attitudes toward risks. This model suggests that risk is not merely a technical calculation of probability, but rather a subjective construct shaped by psychological, social, and cultural factors [3]. The psychometric paradigm adopts a broader and more comprehensive view of risk than statistical models. Specifically, it conceptualises risk as a subjective construct by distinguishing between "experts" (who tend to base risk evaluation primarily on expected number of fatalities) and "lay people" (who rely on a richer and multidimensional understanding of risk). In addition, the model incorporates qualitative characteristics that influence how hazards are perceived, like voluntariness (i.e., whether people choose to be exposed to the risk), immediacy of effect, catastrophic potential (whether the risk may result in many deaths at once). Furthermore, the psychometric paradigm is grounded in a factor analytic approach that identifies three main factors: dread risk, referring to hazards perceived as more threatening than they statistically associated with a stronger desire for stricter societal regulation; unknown risk, which refers to new or poorly understood hazards; and exposure, which is the number of people likely to be affected. Thanks to the consideration of these factors, Slovic et al. developed cognitive maps of hazards, creating "personality profiles" for various technologies or activities based on how they are perceived by the public [2].

We can conclude that risk perception is defined as the subjective judgment that individuals make about the characteristics and severity of a hazard. Risk perception is not determined solely by objective fatality rates but results from a multifactorial assessment of qualitative dimensions, including personal factors.

This theoretical misalignment is empirically evidenced by recent research conducted by Loja and colleagues, which highlights a significant gap between subjective assessment and objective reality [4]. By comparing cyclists' self-reported behaviours (CBQ) and visual assessments against objective risk data (CycleRAP), this study demonstrates that cyclists consistently underestimate extreme-risk scenarios while overestimating low-risk ones. This research is particularly important as it reveals that "expertise" or cycling experience does not necessarily lead to more accurate risk assessments; in fact, frequent cyclists with higher violation and error scores often exhibit the poorest perception accuracy. These findings underscore that because behavioural responses are dictated by this often inaccurate subjective lens, safety interventions must move beyond simple infrastructural fixes to include behavioural strategies that calibrate a cyclist's internal perception to match the objective dangers of the road.

1.2. Risk Perception in Cyclists as a Multidimensional Construct—The Influence of Personal Factors on Risk-Taking Behaviours

Several studies have examined how individual attitudes and behavioural tendencies interact with risk perception among cyclists. For example, Kummeneje & Rundmo (2020) hypothesised that attitudes toward traffic safety and risk-taking behaviour (violation of traffic rules and/or having conflicts with other road users) are influenced by several factors, including dissatisfaction with traffic rules, as well as by geographical context, individual safety attitudes, risk perception (here considered as the assessment of probability and

judgment of severity of consequences) and emotions [5]. The researchers cited the hypothesis of Loewenstein et al., according to which emotions often produce behavioural responses that differ from an individual's cognitive assessment of the most appropriate course of action [6]. This approach acknowledges that behaviour is shaped by the interplay between cognitive evaluation of risk and feelings. Additionally, Loewenstein et al. made a distinction between anticipatory and anticipated emotions: anticipatory emotions are immediate visceral reactions to risk, such as worry, fear, anxiety, and dread, while anticipated emotions are emotions that an individual expects to have as a consequence of a decision. Kummeneje & Rundmo also include risk tolerance as a personal factor that may influence the attitudes people have toward safety [5]. They defined risk tolerance as the extent to which individuals tolerate being exposed to risk when using different modes of transport, so this variable is related to safety priority. In accordance with the previous study by Kummeneje and Rundmo (2018) [7], previous experience of accidents or injury influence cyclists' perception of risk and feeling of worry as well. In particular, individuals who have experienced an accident in the past perceive the probability of being in an accident as higher than individuals who have never had experienced accidents, and they also tend to be more worried about being involved in future accidents.

Their results indicate that cyclists living in urban areas tend to report higher levels of risk-taking behaviour, suggesting that repeated exposure to complex traffic environments may alter both perceived risk and behavioural adaptation. These findings underline the role of social and contextual factors in shaping cyclists' risk-related attitudes.

In their study, Washington et al. observed that riders who perceived cycling as risky were more likely to engage in safety behaviour, such as wearing mandatory helmets and using front lights [8]. They also found that risk perception decreases as cyclist's exposure increases, as measured by riding frequency (days per week) and cycling distance. Finally, the authors suggest that expanding education on cycling practice and traffic rules may contribute to injury prevention.

In addition to attitudes and experience, perceived competence and control have emerged as key psychological factors influencing risk perception. Marín Puchades et al. investigated the relationship between self-perceived cycling competence, near-miss experiences, and risk perception [9]. They found that as perceived control increases, cyclists are more likely to engage in mixed traffic, reflecting a reduced tendency to avoid these traffic conditions. Perceived control may be considered a positive trait, but when such perception exceeds the real control a person has, it should be labelled as overconfidence, which has been found to be related to risk-taking behaviour. According to Marín Puchades and colleagues, cyclists who overestimate their own skills may perceive dangerous or hazardous situations, such as committing a violation, as less risky; moreover, they may feel more capable to deal with them [9].

In this sense, constructs such as self-efficacy and perceived behavioural control play a dual role: they may reduce fear and increase confidence, while at the same time legitimising greater exposure to potentially hazardous situations.

In summary, risk perception in cycling emerges as a multidimensional construct, where the cognitive evaluation of hazards is constantly mediated by visceral emotional responses, more complex affective processes, personality traits and characteristics, past experiences, and a subjective assessment of one's own abilities and control. In addition, individuals continuously recalibrate their sense of safety and their consequent behavioural decisions in response to stimuli from the physical road environment. Consequently, a more nuanced understanding of a cyclist's sense of vulnerability or safety can be achieved by examining not only their subjective risk perception and the various internal factors that shape it, but also how this perception interacts with the external environment.

1.3. Environmental Factors That Influence Risk Perception

As previously noted, beyond individual characteristics, bicycle use is strongly influenced by perceived safety, which is in turn mediated by the urban context and the presence and quality of cycling infrastructure. Perceived safety can be defined as an individual's subjective assessment of how secure and protected they feel within a specific environment. Research conducted in low-cycling contexts has shown that the availability of safe and pleasant cycling infrastructure is a key determinant of bicycle use [10]. The micro-environment has also been proven to have important effects on perceived safety, particularly that the presence of a carefully designed micro-environment (that clearly marks the bicycle's position on the street) and a reduction in traffic volume can improve subjective safety of cyclists [11].

Delclòs-Alió and den Hoed found that potential cyclists are particularly sensitive to infrastructure design, with dedicated facilities and clear spatial separation from motorised traffic being associated with lower perceived risk [10]. Their findings highlighted that infrastructure—particularly when perceived as segregated, recognisable, and safe—plays a critical role in influencing perceptions of cycling environments, even in contexts where cycling is not a predominant mode of transport.

These findings are consistent with research conducted in Dublin, which emphasises the importance of improving routes identified by cyclists as unsafe in order to increase their perceived safety and consequently their cycling levels in large cities [12].

An interesting avenue for further investigation is the perception of safety associated with different bicycle facilities, with particular attention to one environmental feature: lighting. According to Stoll et al. (2024), light segregation refers to the use of physical elements that are intermittently installed alongside cycle lane markings in order to provide cyclists with additional protection from motorized traffic [13]. They found that cyclists tend to reduce their adaptive actions when riding on roads perceived as safe [13]. A possible explanation, according to the authors, is that motorised traffic drivers become more aware of cyclists due to the design changes and their knowledge that crossing a continuous line is not legally permitted. However, as mentioned before, further study on the effect of light segregation is needed to better understand its effect on cyclists' safety behaviour.

Ultimately, these studies suggest that the “urban context” is not merely a backdrop, but a powerful psychological driver. Whether through heavy separation or traffic volume, the physical environment communicates a level of protection that directly dictates how a cyclist feels and behaves on the road. This may help to gain a broader understanding of how these perceptions shape urban mobility as a whole.

1.4. How Risk Perception Shapes Transportation Mode Choice

Risk perception has also been theorised as a decisive factor linking environmental conditions to transport mode choice [14]. Within behavioural decision-making frameworks, perceived risk can act either as psychological cost that may outweigh instrumental benefits and attitudes (such as travel efficiency, convenience, or environmental sustainability) or as a driver of change towards different habits. In a cross-sectional study conducted during the temporary closure of a major inner-city road bridge, Kemmerer found a strong association between perceived health risk (due to air pollution) and the likelihood of switching to cycling [15]. According to this research, transport mode choice is a habitual behaviour, performed automatically; as stated in the Habit Discontinuity Hypothesis [16], when the context in which the habitual behaviour occurs changes, people are more likely to reflect on their mode choice; however, making a change typically requires a strong concern for their health. Kemmerer et al.'s results indicated that individuals with higher health-related risk perception were more likely to switch from cars to alternative modes during the closure.

Constructs from the Theory of Planned Behavior (Ajzen, 1991)—including attitude toward the behaviour, subjective norms, and perceived behavioural control—were not associated with switching [17]. However, these constructs did predict whether individuals persisted in using either alternative modes or cars before and during the bridge closure.

On the other end, Wang et al., in their research on the diffusion of public bicycle systems in Beijing (China), highlighted that perceived risk plays a critical role in shaping users' switching intentions, often acting as a barrier to adoption despite the availability of shared cycling infrastructure [18]. Their results indicated that higher perceived risk reduces the likelihood of adoption, despite the availability of cycling infrastructure. Conversely, when potential users can observe others successfully using the system, perceived risk decreases, thereby increasing the probability of adopting public bicycles.

Taken together, these studies underscore that risk perception is a multifaceted psychological lever in the decision-making process. In the final analysis, the transition to cycling is not merely a matter of providing physical infrastructure, but of navigating a complex interchange where the perceived benefits of a new mode must consistently outweigh the psychological costs of the risks involved, reinforcing the importance of addressing perceptual and cognitive barriers in cycling promotion strategies.

1.5. Barriers in Cycling Promotion

Evidence consistently shows that cyclists' attitudes toward traffic safety and their perceived levels of risk are strong predictors of risk-taking behaviour and engagement in cycling activities [5]. In a similar vein, Rasch et al. (2022) showed that perceived safety in overtaking manoeuvres is heavily influenced by cyclists' subjective evaluations of factors such as lateral clearance and vehicle speed, highlighting that perceived and objective indicators of safety do not always coincide [19]. Consequently, even when infrastructural changes reduce crash risk or enhance traffic conditions, individuals may continue to perceive cycling as unsafe if their personal risk assessment remains elevated.

Beyond safety perceptions, the promotion of cycling is also affected by individual attributes (e.g., income, occupation) and travel attributes (e.g., usage costs, speed, satisfaction). For instance, Li and colleagues found that satisfaction with current e-bike usage positively influences continued usage intention, while increased usage costs and reduced speed—particularly for delivery personnel—negatively affect it, highlighting the importance of economic and performance-related factors in sustaining cycling-based mobility [20].

Furthermore, studies examining safety perception in urban contexts found that perceived safety plays a central role in shaping willingness to cycle and overall comfort in traffic environments [11,12,21].

Interventions aimed solely at modifying the built environment may therefore be insufficient unless accompanied by efforts to influence risk communication, enhance perceived control and competence, and foster more positive safety-related attitudes. Promoting cycling uptake requires not only objective safety improvements but also targeted strategies that acknowledge the psychological processes underlying risk perception and decision-making in transport behaviour.

While previous research has shed light on the relationships between perceived risk, infrastructure, individual characteristics, and mode choice, less attention has been devoted to understanding how these perceptions may be leveraged in order to actively encourage cycling uptake. In particular, there is a need for studies that integrates behavioural and perceptual dimensions to identify factors capable of reducing psychological barriers to cycling. Addressing this gap, the present study aims to investigate cyclists' behaviours with a specific focus on risk perception, examining how individual, contextual, and experiential

factors interact and influence cycling-related decisions and cyclists' risky behaviour. More specifically, building on the distinction between objective risk and perceived risk as well as on evidence from the Psychometric Paradigm [2], this study aimed to test two hypotheses:

- (a) Risk perception plays a central role in shaping cycling behaviour.
- (b) Individual and experiential factors, specifically pro-environmental attitude and cycling expertise, differentially predict distinct behavioural outcomes, particularly errors versus violations.

2. Materials and Methods

2.1. Objectives

The aim of the present study is to understand how pro-environmental attitudes, risk perception skills, and cycling frequency influence cyclists' risky behaviour in urban contexts, with particular attention to the distinction between cycling errors (unintentional failures) and cycling violations (deliberate rule-breaking). While both behaviours increase accident risk, they may arise from different psychological mechanisms—automatic and perceptual processes for errors versus deliberative and motivational processes for violations.

Consequently, this hypothesis has been formulated: people who have a less accurate risk perception are more prone to making violations while riding a bike, and so people who make less errors in identifying the sources of risks in the streets will make less violations while riding.

2.2. Participants

Respondents were recruited using a snowball method via WhatsApp and email; in the end 105 people answered and filled out the questionnaire, of which only 100 were found to satisfy the inclusion criteria. All subjects were unpaid volunteers aged between 18 and 83 (average age $M = 39,04$ and standard deviation $DS = 16,75$); 64 of them were female and 36 were males.

Specifically, the age distribution was as follows: 20% aged 18–25, 28% aged 26–40, 24% aged 41–55, 20% aged 56–70, and 8% aged 71–83. Regarding education, 50% held a high school diploma, 41% a university degree, 2% a postgraduate degree, and 7% a middle school diploma. Regarding cycling frequency: 12% of participants reported cycling daily, 28% weekly, 24% monthly, and 36% less than once per month.

All the participants were Italian; most of them came from Lombardy (83). Participants were eligible if they met the following criteria: being 18 years or older; being able to ride a bicycle and feeling confident while cycling; being resident in urban or peri-urban areas, where interaction with traffic and environmental infrastructure is relevant and reporting regular bicycle use, defined as cycling at least once per month in real-world settings (e.g., commuting, leisure, or utility cycling) over the past two years. Participants were excluded if they met any of the following conditions: being non-cyclists or reporting extremely occasional bicycle use (i.e., less than once per month); being professional or competitive cyclists; having a self-reported history of severe anxiety disorders (including specific phobias related to mobility); having physical conditions that prevent bicycle use; presenting conditions that significantly affect risk perception (e.g., cognitive impairments); recent involvement in a serious cycling accident (within the past 3–6 months), due to the potential impact on risk perception. As a result of these criteria, “cycling expertise” in the present study is operationally defined as self-reported frequency of bicycle use, capturing everyday riding experience rather than professional or competitive training.

2.3. Procedures

The study received approval from the local ethics committee and followed the principles of the Declaration of Helsinki. All participants provided their informed consent.

Five instruments were selected to compose the survey. These were adapted to the research context through translation from English into Italian and by adjusting the vocabulary accordingly. In addition, photographs were taken in selected environments and used to assess participants' levels of risk perception; two images were ultimately selected as the most suitable for the purpose of creating a static hazard perception test.

Following the development of the questionnaire, a pilot study was conducted to evaluate completion time and ensure clarity and comprehensibility of the items.

The questionnaire was then administered online via Google Forms between 2 and 13 November 2021. Finally, the data were analysed using Jamovi 2.7.26.

2.4. Measures

The administered questionnaire consisted of four sections: (1) demographic information; (2) mobility habits; (3) the Cyclists' Behaviour Questionnaire (CBQ); (4) two subscales of the Environmental Attitudes Inventory (EAI)—personal conservation behaviour and ecocentric concern. In addition, participants completed a static hazard perception task involving six images of cycling environments with potential hazards. Each image was divided into 16 quadrants, and participants were asked to indicate which quadrants contained potential risks for a cyclist.

2.4.1. The Cyclists' Behaviour Questionnaire (CBQ)

The CBQ [22] is a self-report instrument that measures cyclists' behaviour by assessing both highly risky (errors and violations) and positive riding behaviours. It was structured based on the Driving Behaviour Questionnaire by Reason et al. [23], which assesses the behaviours of motor vehicle drivers. The CBQ is a Likert scale consisting of 44 items divided into three categories: Violations (V), 16 items; Errors (E), 16 items; and Positive Behaviours (PB), 12 items. The response scale is five-point: 0 = never; 1 = almost never; 2 = sometimes; 3 = frequently; 4 = almost always.

2.4.2. Environmental Attitudes Inventory (EAI)

The Environmental Attitudes Inventory EAI [24], was developed based on the Environmental Attitudes (EA). The EAI measured 12 main factors related to two-dimensional structures, preservation and utilisation. Preservation attitudes express the belief that the conservation of nature should be a priority, while utilisation attitudes indicate the belief that the use of all-natural resources for human goals is proper and necessary. Twelve subscales were developed, each one comprising 10 items: (1) enjoyment of nature, (2) support for interventionist conservation policies, (3) environmental movement activism, (4) conservation motivated by anthropocentric concern, (5) confidence in science and technology, (6) environmental threats, (7) altering nature, (8) personal conservation behaviour, (9) human dominance over nature, (10) human utilisation of nature, (11) ecocentric concern and (12) support for population growth policies. We used two subscales in this study, "personal conservation behaviour" and "ecocentric concern", because they are most aligned with the objectives to be achieved. The responses to all measures were given on a 7-point Likert rating scale, ranging from 1 (strongly disagree) to 7 (strongly agree).

2.4.3. Static Hazard Perception Test

Ten photographs of urban and suburban road environments were taken from the cyclists' perspective, depicting crossings, roundabouts, intersections, and cycle paths. Two

pictures were selected as the most representative of typical urban cycling scenarios. Participants were then asked to observe the images as if they were cycling and to identify, based on their personal judgment, any potential sources of risk. A grid was superimposed on each image, dividing them into sixteen quadrants; participants indicated, using letters (A–D) for columns and numbers (1–4) for rows, which quadrants, in their opinion, contained a potential source of risk for cyclists. This task was developed with reference to the line of research on static hazard perception tests [25,26] for drivers and other road users [27], which are used to assess abilities such as the capacity to detect potential sources of risk in the environment, visual behaviour, and environmental awareness. Across the two selected images, a total of 10 quadrants contained verifiable sources of high risk for cyclists (e.g., vehicle conflict zones, poor visibility areas), as independently rated by two researchers. Inter-rater agreement was 92%, with a Cohen's Kappa of 0.87; disagreements were resolved through discussion with a third expert to produce a final answer key. Participants' responses were coded as correct or incorrect, and the index of adequate risk perception was computed as the total number of correctly identified hazardous quadrants.

2.5. Data Analysis

Three Bayesian linear regression analyses were conducted using the jsq module in Jamovi (version 2.3.28) to examine the contribution of each predictor to the three CBQ subscales, which were entered as dependent variables. The predictors included gender, frequency of bicycle use, the two EAI subscales, and the index of adequate risk perception. Model comparison was based on Bayes factors (BFs), with the strength of evidence assessed by comparing each candidate model against the null model. For each analysis, posterior estimates, 95% credible intervals (CrIs), and inclusion Bayes factors were examined to evaluate the contribution of individual predictors.

3. Results

Results are reported separately for each dependent variable (the three CBQ subscales: Positive behaviour, Errors, and Violations) (Table 1).

Table 1. Bayesian linear regression results for each CBQ subscale.

Dependent Variable	Best Predictor	BF ₁₀	R ²	BF_Inclusion	p(incl Data)	Posterior Mean (M)	95% CrI
Positive behaviour	Personal Conservation Behaviour	12.82	0.09	18.84	0.95	0.37	[0.12,0.62]
Errors	Adequate risk perception index	1.21	0.04	1.98	0.66	0.13	[−0.01,0.26]
Violations	Frequency of bicycle use	59.07	0.12	23.16	0.96	−2.24	[−3.51,−0.97]

Note: BF₁₀ = Bayes factor comparing the model including the predictor to the null model; R² = proportion of variance explained; BF_inclusion = inclusion Bayes factor for the predictor; p(incl | data) = posterior inclusion probability; CrI = 95% credible interval.

3.1. Positive Behaviour

Model comparison indicated that the model including the Personal Conservation Behaviour subscale (EAI) provided the best fit to the data relative to the null model (BF₁₀ = 12.82), suggesting strong evidence in favour of this model. The model explained a modest proportion of variance (R² = 0.09). Adding additional predictors did not substantially improve model performance. Inspection of posterior estimates showed that Personal Conservation Behaviour was positively associated with the dependent variable (M = 0.37, SD = 0.13, 95% CrI [0.12, 0.62]). The inclusion Bayes factor indicated strong evidence for this predictor (BF_inclusion = 18.84), with a high posterior inclusion probability (P(incl | data) = 0.95).

3.2. Errors

Model comparison indicated that the model including adequate risk perception index was only slightly better supported than the null model, $BF_{10} = 1.21$, indicating anecdotal evidence in favour of the model. The explained variance was low, $R^2 = 0.04$. Examination of posterior estimates showed that adequate risk perception index was weakly and positively associated with the dependent variable, $M = 0.13$, $SD = 0.07$, 95% CrI $[-0.01, 0.26]$. However, the credible interval included zero, suggesting substantial uncertainty regarding the direction and magnitude of the effect. Consistently, the inclusion Bayes factor indicated only weak evidence for this predictor, $BF_{inclusion} = 1.98$, with a moderate posterior inclusion probability, $P(incl | data) = 0.66$.

3.3. Violations

Model comparison indicated that the model including frequency of bicycle use was best supported relative to the null model, $BF_{10} = 59.07$, providing strong to very strong evidence in favour of this model. The model explained a modest proportion of variance, $R^2 = 0.12$. Including additional predictors did not substantially improve model support. Posterior estimates indicated that frequency of bicycle use was negatively associated with violations, $M = -2.24$, $SD = 0.64$, 95% CrI $[-3.51, -0.97]$. The inclusion Bayes factor showed strong evidence for this predictor, $BF_{inclusion} = 23.16$, with a high posterior inclusion probability, $P(incl | data) = 0.96$.

4. Discussion

The present study aimed to extend existing research by integrating behavioural and perceptual dimensions in the analysis of cyclists' conduct, with a particular focus on the role of risk perception. Building on the theoretical framework outlined in the Introduction, particularly the distinction between objective and perceived risk, as well as evidence from the Psychometric Paradigm, it was expected that (a) risk perception would play a central role in shaping cycling behaviour, and (b) individual and experiential factors, specifically pro-environmental attitude and cycling expertise, would differentially predict distinct behavioural outcomes (i.e., errors versus violations). Overall, the findings provide only partial support for these expectations and suggest that the relationship between perception, motivation, and behaviour is more complex than initially assumed.

First, the present study extends prior work on pro-environmental behaviour by showing that individuals who report higher engagement in environmentally responsible actions also tend to adopt more virtuous cycling practices. This is consistent with previous research indicating that behaviours across domains may be driven by shared motivational orientations, such as prosocial values, sense of responsibility, and norm adherence (Nguyen et al., 2023) [28–30]. In contrast with mode switching, which is often habitual and constrained by infrastructure, positive cycling behaviours such as signalling or using lights are deliberate, rule-governed actions. These behaviours are therefore more likely to be shaped by reflective, System 2 processes translate pro-environmental values into specific virtuous actions. This may explain why pro-environmental attitudes emerged as predictors, whereas they often fail to predict automatic or context-dependent choices like mode shift.

A similar interpretation is in line with the Theory of Planned Behavior, according to which general attitudes and normative beliefs may influence behaviour across different domains [17]. However, this result should be interpreted with caution. The observed association should not be considered as evidence of a direct causal relationship. One possible explanation is that pro-environmental behaviours and safe cycling behaviours respond to partially different functional goals—environmental protection on the one hand and risk management on the other. From a theoretical perspective, this pattern is compatible

with dual-process accounts [31], suggesting that higher-order, deliberative processes (e.g., values and norms) may produce consistent behavioural tendencies across domains without necessarily leading to uniform behavioural outcomes [31]. Second, contrary to expectations derived from the prior literature [1,5], no robust evidence emerged for a direct association between risk perception and cycling errors [1,5]. Credibility intervals included zero, and Bayesian evidence for the effect was weak ($BF_{10} = 1.21$), indicating limited support for a direct relationship. This null finding likely reflects the operationalisation of risk perception as hazard identification accuracy in static scenes, which captures cognitive-perceptual awareness rather than the subjective affective dimensions of risk perception—such as dread and worry—emphasised by the Psychometric Paradigm. Because cycling errors are largely automatic and unintentional, declarative knowledge of hazards alone may not be sufficient to prevent them. Furthermore, cyclists with greater hazard awareness may notice and self-report more of their own errors, potentially masking any protective effect.

An additional explanation is that individuals with higher hazard awareness may be more likely to notice and report their own mistakes, potentially attenuating observable associations. Overall, these results suggest that risk perception may influence behaviour in a more indirect and context-dependent manner than often assumed, potentially mediated by emotional responses, perceived control, or situational demands [6,9,32]. From a dual-process perspective, errors are more likely to arise from fast, automatic processes (System 1), such as attentional lapses and perceptual constraints, which operate independently of reflective risk evaluation (System 2). Consequently, even individuals with high hazard recognition skills may still commit errors in real-world cycling.

Moreover, the hypothesis that risk perception plays a pivotal role in cycling behaviour was not supported; this null finding may partly stem from the static nature of the hazard perception measure, which captures conscious environmental awareness rather than the dynamic, real-time risk processing required in actual cycling.

Third, cycling experience emerged as a protective factor against violations but not against errors. The negative association between cycling frequency and violations may reflect two complementary mechanisms. First, frequent practice may automatise rule-compliant riding behaviours, transforming deliberate compliance into overlearned habits that reduce the impulse to violate. Second, greater experience may enhance perceived competence, leading cyclists to anticipate and manage traffic demands more effectively and thus feel less need to bend rules to maintain safety or progress.

This finding is consistent with previous research suggesting that violations are primarily shaped by deliberate decision-making processes, such as cost–benefit evaluation and norm compliance [5,33]. In contrast, the absence of a protective effect on errors highlights a limitation of experience-based learning. In line with dual-process models, errors are more likely to arise from automatic processes (System 1), including attentional lapses and perceptual constraints, which are not necessarily mitigated by increased experience. Previous research in related domains suggests that expertise may, under some conditions, lead to behavioural automation and reduced vigilance [34,35]. Therefore, while experience may improve efficiency and rule adherence, it does not eliminate the intrinsic limitations of the cognitive system. This distinction further supports the importance of differentiating between behavioural types when examining safety outcomes.

Taken together, the present findings suggest that different behavioural outcomes in cycling are associated with partially distinct psychological mechanisms. Violations appear to be influenced by deliberative processes and experiential learning, whereas errors seem to be more closely related to automatic cognitive processes. These differences indicate that distinct explanatory models and intervention strategies may be required.

This study has several limitations. First, the hazard perception measure relied on static images and explicit identification of hazards, capturing conscious environmental awareness rather than dynamic real-time processing. This limits ecological validity and may partially explain the weak predictive power observed for errors. The use of only two images further reduced variability and sensitivity, likely contributing to limited statistical evidence ($BF_{10} = 1.21$). Future studies should adopt more ecologically valid approaches, such as video-based or VR paradigms, to better capture real-world cycling cognition.

Second, the relatively low explained variance across the models suggests that relevant predictors of cycling behaviour were not included. Variables such as personality traits, emotional responses, and contextual characteristics (e.g., infrastructure design) have been shown to play an important role in shaping cycling behaviour [9,10,13].

In addition, the relatively small sample size may have limited statistical power, increasing the likelihood of Type II errors. Furthermore, the sample was predominantly female (64%) and from the Lombardy region (83%). Given that gender and regional infrastructure both shape perceived safety and cycling behaviour, the findings may not generalise to male cyclists or to areas with different cycling environments and cultural norms. Future studies should aim for more balanced samples across gender and Italian regions.

From a practical perspective, the present findings suggest several implications, although these should be interpreted with caution. The association between pro-environmental and virtuous cycling behaviours indicates that interventions leveraging shared motivational drivers—such as responsibility and prosocial values—may be effective [28–30]. Second, cycling frequency emerged as a protective factor specifically against violations, suggesting that promoting regular, gradual exposure to cycling in low-risk contexts may help automatise correct behaviours and reduce deliberate infractions.

However, the limited role of risk perception in predicting errors suggests that interventions exclusively centred on risk awareness may be insufficient, particularly when unsafe behaviours arise from automatic attentional and perceptual processes rather than deliberate decision-making. Instead, strategies should also target automatic and situational processes, such as attentional demands and environmental design, in line with research on perceived safety and infrastructure [11–13].

Future research should build on these findings by adopting more ecologically valid methodologies, such as dynamic simulations or naturalistic observations, to better capture real-world behaviour. In addition, larger and more diverse samples will be necessary to improve generalisability and to examine potential moderating effects. Moreover, while the present study focused on main effects of cycling frequency, pro-environmental attitudes, and CBQ dimensions, future studies with larger samples should systematically investigate interaction effects among these predictors (e.g., cycling frequency $\times$ risk perception, pro-environmental attitudes $\times$ habitual automaticity), as such interactions could reveal important conditional mechanisms that our sample size ($N = 100$) was underpowered to detect. Finally, integrating cognitive, emotional, and contextual variables within a comprehensive framework may provide a more complete understanding of how risk perception interacts with other factors to shape cycling behaviour and transport mode choice [15,18].

5. Conclusions

This study aimed to examine the role of risk perception and pro-environmental attitude in shaping cyclists' behaviour, responding to the need—highlighted in the previous literature—to better integrate perceptual and behavioural dimensions in the analysis of cycling practices. In doing so, it contributes to a more comprehensive understanding of the mechanisms underlying both cycling safety and the promotion of sustainable mobility.

Overall, the findings suggest that unsafe cycling behaviours cannot be explained through a unitary model of risk perception. Rather, different behavioural outcomes—particularly violations and errors—appear to rely on partially distinct psychological mechanisms. Risk perception did not emerge as a robust predictor of cycling errors, indicating that increasing individuals' awareness of risk may not be sufficient to reduce unsafe behaviours. This result supports a perspective in which different psychological processes contribute to different behavioural outcomes.

At the same time, the association between pro-environmental behaviours and virtuous cycling practices indicates that behavioural consistency across domains may be rooted in shared motivational orientations, such as prosocial values and sense of responsibility. This finding reinforces the idea that cycling behaviour should be considered within a broader system of attitudes and values related to sustainability and social responsibility.

The selectivity of this association—with pro-environmental attitudes predicting positive behaviours but not errors—further supports the distinction between deliberative and automatic processes. Pro-environmental values, as measured here, likely operate through reflective (System 2) pathways to motivate intentional, rule-governed actions, whereas errors arise from more automatic (System 1) perceptual motor routines that are largely insensitive to explicit environmental attitudes. This pattern suggests that environmentalism fosters a motivational orientation toward safer cycling rather than enhancing the perceptual skills needed to avoid unintended mistakes.

From a practical perspective, these findings have relevant implications for cycling promotion strategies. Interventions aimed at increasing cycling uptake should not rely exclusively on improving risk awareness but should also address the cognitive and contextual factors that influence behaviour in real-world settings. In particular, strategies targeting automatic processes—such as improving infrastructure design, reducing environmental complexity, and supporting attentional demands—may be more effective in reducing errors. At the same time, communication campaigns emphasising the environmental and social benefits of cycling may help reinforce norm-consistent and responsible behaviours.

Finally, this study highlights the importance of adopting a multidimensional and integrative approach to the study of cycling behaviour. Future research should further examine the interplay between cognitive, emotional, and contextual factors using ecologically valid methodologies and more diverse samples. This approach may support the development of more effective and targeted interventions, contributing to safer and more sustainable urban mobility systems.

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