Transportation Research Part F: Psychology and Behaviour 114 (2025) 1115–1128

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Cycling under stress: Analysing the impact of sociodemographic and psychological factors on cyclists' perceived safety: A German example

C. Schmidt-Hamburger [a,*], D. Agola [b], C. Hamel [b], P. Zeile [a], N. Haug [a,1]

[a] *Karlsruhe Institute of Technology, Professorship of Urban Neighbourhood Planning (STQP), Germany*
[b] *University of Stuttgart, Institute of Human Factors and Technology Management (IAT), Germany*

ARTICLE INFO

Keywords:
Cycling safety
Vulnerable groups
EmoCycling
Psychophysiological measurement
Age factors
Germany

ABSTRACT

This study investigates factors influencing cyclists' perceived safety utilizing the EmoCycling methodology to identify 'Moments of Stress' (MOS). The research collects physiological data from 143 participants across three German cities (Herrenberg, Ludwigsburg, and Osnabrück) between 2022 and 2024, with 90 observations ultimately included in the statistical analysis. Participants are equipped with empatica E4 wristbands measuring electrodermal activity and skin temperature during cycling activities. Logistic regression analysis examines relationships between MOS and Geller's cyclist typology, psychological traits, and sociodemographic variables.

Results indicate that age is the sole significant predictor of elevated MOS, with participants aged 50 years or older demonstrating 3.54 times higher odds of experiencing physiological stress responses while cycling ($p < 0.05$). Contrary to hypothesized relationships, the categorization of cyclist typology, personality traits, and gender variables do not yield statistically significant associations with stress levels.

These findings suggest that age-related factors may outweigh other variables in determining the physiological stress response during cycling activities. This exploratory study provides initial evidence on cyclists' physiological stress responses and their correlation with age-related factors, establishing a foundation for subsequent investigations into the complex interactions that affect cyclists' stress experiences in urban environments.

1. Introduction

The German government's investment in promoting cycling from 2020 to 2023 highlights the recognition of cycling's multifaceted benefits for health, the environment, and society. Despite these efforts, socially exclusive mechanisms such as the gender mobility gap persist (Gauvin et al., 2020), emphasising the need for inclusive cycling infrastructure planning that considers vulnerable groups (BMDV, 2022). Persistent mobility gender gaps prevent women and other marginalized groups from accessing education, jobs, and healthcare, limiting not only their individual potential but also holding back economic growth. Closing these gaps would create a double benefit: empowering women to participate fully in society while advancing environmental goals, since women typically use

* Corresponding author.
E-mail address: celine.schmidt-hamburger@tuwien.ac.at (C. Schmidt-Hamburger).
[1] All authors contributed equally to this work.

https://doi.org/10.1016/j.trf.2025.07.004
Received 1 April 2025; Received in revised form 27 May 2025; Accepted 2 July 2025
Available online 17 July 2025

more sustainable transport options that can influence broader shifts away from private vehicles (World Bank, 2024).

While various studies categorise cyclists into subgroups, there is a lack of typologies considering safety perception, which is crucial for identifying vulnerable groups (Anke et al., 2021; Félix et al., 2017).

In this context, perceived safety and stress play a central role: Research shows that heightened stress levels while cycling is negatively associated with both the intention to cycle and actual cycling frequency (Avila-Palencia et al., 2017). However, this is a plausible correlation, as individuals are more inclined to adopt and integrate a mode of transport into their daily routines when they perceive it as safe and comfortable. This effect is particularly pronounced among risk-averse individuals or those with limited cycling experience (Geller, 2006). These findings highlight the practical importance of taking a closer look at stress in cycling contexts, as reducing perceived stress could directly contribute to increasing bicycle use.

The approach used in the present study involves collecting psychophysiological signals close to the body. We precisely measure autonomic nervous system (ANS) responses such as electrodermal activity (EDA) with the Galvanic Skin Response (GSR) and skin temperature. With these signals, it is possible to measure responses to heightened negative attention, colloquially referred to as 'stress'. This physiological perspective provides an objective foundation to complement existing, predominantly descriptive or infrastructure-focused approaches to understanding cyclist stress. Several studies, therefore, have already attempted to analyse the phenomenon of stress in the context of cycling – albeit with different methodological approaches and focal points. The following section outlines the most important studies.

Roger Gellers' (2006) four types of cyclists include differences in stress tolerance within different bicycle subgroups but only mention them descriptively. Caviedes and Figliozzi (2018) further concluded that bicycle studies lack stress-related data. Their paper focussed more on the causes of stress due to traffic conditions and traffic-related infrastructure in a US city, whereas in a Central European city the causes of negative arousal when cycling may well be influenced by other factors in the built environment. According to Schandry (2016), subjective-psychological conditions influence stress reactions more than objective-physical ones, highlighting the importance of individual perceptions in stress responses. Building on this understanding, research has identified several key individual difference factors that shape how people experience and cope with stress. The perceived locus of control represents one such critical factor, as it directly influences how individuals interpret and respond to stressful situations. Additionally, personality traits play a fundamental role in stress management, with individuals exhibiting varying traits on the Big Five Scale (Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism) demonstrating distinct approaches to coping with external stressors (Penley & Tomaka, 2002; Vollrath, 2001). Furthermore, demographic characteristics contribute to stress vulnerability, as research indicates that non-male individuals (Schulz et al., 2002) and older adults are more susceptible to experiencing stress (Schoon, 2010). Given that these psychological, personality, and demographic factors collectively influence stress responses and coping mechanisms, they represent essential variables for understanding individual differences in stress experiences and therefore warrant inclusion in our comprehensive analysis.

The research aims to understand factors affecting cyclists' perceived safety using the EmoCycling mixed methods approach to identify and analyse 'Moments of Stress' (MOS) in German bicycle infrastructure (Zeile et al., 2023).

The study employs logistic regression to identify vulnerable groups among bicycle users. This approach investigates the relationship between the number of MOS and (a) Gellers' four types of cyclists, (b) psychological personality traits, and (c) sociodemographic factors.

2. Theoretical framework and State of research

In our research, we employ the concept of triangulation to examine our subject from multiple perspectives. Unlike mixed methods, which primarily focus on combining qualitative and quantitative approaches, triangulation connects different data sources, methodological approaches, and theoretical perspectives to enhance understanding and avoid blind spots (Flick, 2009).

2.1. Stress – An emotional construct

Operationalizing stress presents significant complexity due to its interdisciplinary nature. Current stress research encompasses various conceptualizations (Kaluza, 2007), distinguishing between positive (eustress) and negative (distress) stimuli (Schmidt, 2021). Different theoretical frameworks of stress differ in their approaches to adaptive capacity and operationalizability. Stress emerges when physiological (stress as response) or psychological (stress as stimulus or transaction) systems must mobilize resources for processing, depending on the theoretical framework employed (Bercht, 2013). The transactional stress model proposed by Lazarus (1999) remains the most prominent framework. However, it presents the highest complexity due to its conceptualization of stress as an emergent situation arising from interactions between humans and their environment. In contrast, response-based stress models (Cannon, 1932; Selye, 1956) form the foundation of contemporary psychophysiological stress research, examining physiological responses to external stimuli. A critical limitation of this approach lies in its assumption of uniform stress responses across individuals (Lyon, 2005). The third theoretical paradigm, which conceptualizes stress as a stimulus, emphasizes its psychological implications. This framework posits the existence of "critical life events" (Holmes & Rahe, 1967) that objectively induce varying degrees of stress. For measurement purposes, Holmes and Rahe developed a comprehensive scale. Given recent developments in 'emotion sensing', the theoretical foundation of this work aligns more closely with response-based stress models while incorporating subjective components into data collection and analysis.

Table 1
Types of cyclists.

Group	The strong and fearless cyclists	The enthusiastic and confident (Everyday cyclists)	The interested but concerned (Interested cyclists)	No chance, no matter what
Characteristics	· cycles always · safely, confident	· drives daily routes medium safety needs · confident,	· no everyday cycling toward bicycles · safety concerns · open-minded	· no cycling in general
Riding skills	Excellent control of the bicycle	Confident, partly defensive because of security	Less confident	Poor control of the bicycle, lack of riding experience
Stress tolerance	high	medium	low	very low

Note. Own presentation based on Geller (2009).

2.2. Emotion Sensing and EmoCycling method

The method of recording biostatistical data in a georeferenced manner originated from Christian Nold's (2009) concept of "emotional cartography," which first captured arousal states within an urban context. This approach was later expanded to cycling, as described by Teixeira et al. (2020) providing a comprehensive overview of both "stress while cycling" and general approaches to measuring stress.

The concept of "EmoCycling" (Zeile et al., 2016) emerged from the Urban Emotions Initiative and was refined through various technological adjustments (Kyriakou et al., 2019; Moser et al., 2023). The method measures negative arousal by using two biological indicators:

- Skin temperature (ST)
- Skin conductance (EDA)

When confronted with a stressor, the human organism regulates endogenous stress responses, resulting in increased skin conductance (EDA) and decreased skin temperature (Kyriakou & Resch, 2019; Schandry, 2016). Based on these biosignals, an algorithm was developed to detect people's Moments of Stress (MOS).

2.3. Sociodemographic and psychological factors affecting stress

Endogenous factors significantly influence the magnitude of stressor effects, encompassing demographic, socioeconomic, and sociocultural attributes (Wermuth, 2005). For the present study, the particularly relevant factors include:

a) Gender: Research indicates that gender has a significant influence on stress perception patterns. Studies suggest that women typically manifest stress responses more readily than men (Dörrzapf et al., 2014; Kyriakou et al., 2019).

b) Age: Differences in environmental perception and ambulatory velocity patterns indicate vulnerability among children (up to 14 years old) and elderly individuals (over 70 years) in traffic situations. Evidence suggests that advanced age typically correlates with increased susceptibility to negative stress perception (Ausserer, Füssl & Risser, 2013; Schoon, 2010).

c) Psychological characteristics: Traditionally, the personality of individuals is determined based on the so-called 'Big Five', which consists of the traits of extraversion, neuroticism, openness, conscientiousness, and agreeableness. The Big Five are recognized for their strong predictive power in various aspects of life, including the mobility domain, where they help explain mobility behaviours (Lim et al., 2023). The level of control beliefs describes a person's belief that he or she has control over various situations and that these are the result of his or her actions (internal) or that fate, coincidences, or powerful others are responsible for the occurrence of certain events (external) (Beierlein et al., 2014; Kovaleva et al., 2012; Rammstedt et al., 2012). The degree of control belief is a relevant factor in the evaluation of a stress reaction (Brosschot et al., 1994).

2.4. Type of cyclists

From a biopsychological perspective, there is evidence suggesting that genetic or psychological predispositions can either amplify or alleviate stress responses (Ingram & Luxton, 2005). Depending on their predisposition, experiences, or access to alternative modes of transport, cyclists tend to assess situations differently (Paschalidis et al., 2016). According to Geller (2006), cyclists can be categorized into four groups: "the strong and fearless," "the enthusiastic and confident," "the interested but concerned," and "no chance, no matter what". Table 1 provides an overview of these characteristics. It is important to note that the boundaries between these groups are dynamic. Regarding cycling promotion, research should mainly focus on the stressful experiences of the "interested but concerned" group, as they represent potential regular cyclists who safety concerns may deter..

To improve the classification of the participating cyclists, the presented approach adopted and slightly modified the taxonomy of Robert Geller (2009) (see Table 1).

Table 2
Literature synopsis.

Authors	Country	Use-case	Study Design	Variables	Method	Sample Size	Results
Varet et al., 2025	France	Cyclists	Survey	General risk propensity; impulsive behaviour; perceived legitimacy of traffic rules; risk perception of bicycle crashes; social norms associated with cycling behaviours; frequency of helmet use, mobility and psychosocial variables	bivariate and multivariate analysis, mediation analysis	1650	General risk propensity is associated with more violations, errors, and involvements in past crashes; Descriptive norms associated with violations, errors, helmet use and involvement in past crashes; Risk perception very little influence on cycling behaviours
Fenerich et al., 2024	Brazil	Home-to-work commuter	Survey, Machine Learning	Accuracy; Precision; Negative predicted value; Traffic stress	Machine learning; classification	196	Logistic regression has highest total success rate (TAT);TAA was greater in all three classifier algorithms than TAB
Luo et al., 2023		Health and regeneration	Meta Analysis	Stress, Big Five personality traits	Structural Equation Modelling	250 studies; Total sample size: 158,232	Neuroticism positively relates to stress; extraversion, agreeableness, conscientiousness and openness are negatively linked to stress; All big 5 personality traits significantly associate with physiological stress perception
Oehl et al., 2019	Germany	Cyclists	Survey	Anger experience of cyclists;Expression of anger	Component Analysis; Factor Analysis	421	Cycling anger decreases with higher age, Male cyclists significantly more angered by police interaction and interactions with other cyclists than female cyclists
Caviedes & Figliozzi, 2018	Portland, USA	Cyclists	Explorative Design	Galvanic Skin Response (GSR), types of bicycle infrastructure, traffic volume	Data visualization; Two paired t-tests	5	Higher average stress level during peak hours, on intersections and along on-street facilities
Marois et al., 2018	Canada	Traffic workers	Self-report; Observation; Physiological measures	DAS (dichotomous anchored stress)	Binomial logistic regression; Multifactorial logistic regression; Correlation analysis	19	Stress level associated with being on task, working on construction site, being on a site with 1 to 4 lanes of construction, high car traffic and high pedestrian traffic
Pesle et al., 2018)	France	Car drivers	Online survey	Mood; Big Five personality; Driving style; Weekly stress inventory; Coping	Multiple Correspondence Analysis	218	Driver profiles; Age, gender, personality, accident involvement and driving experience influence driving styles and stress vulnerability; Young male drivers are more likely to drive aggressively and take risks
Matthews et al., 1991	United Kindgom	Car drivers	Survey	Study 1: Driver stress and personality dimensions extraversion, neuroticism, psychoticism	Study 1: Two factor analysis	study 1: 159	study 1: General driver stress correlates positively with the EPQN scale, n as strongest predictor of driver stress, age as a strong confounding factor
				Study 2: Intra-personal and situational frustration and annoyance in driver stress	Study 2: Partial correlation	Study 2: 44	Study 2: Driver stress and frequency of daily hassles and aggressiveness correlates positively
				Study 3: Driver stress, individual differences in self-reported attentional efficiency	Study 3: Partial correlation	Study 3: 49	Study 3: Higher driver stress is related to poorer self-rated attention
				Study 4: Driver stress and mood in situations un/ related to driving	Study 4: Partial correlation	Study 4: 50	Study 4: Driver stress associated with stressed mood states in experimental and control group

Table 3
Data overview of the physiological measurements in the three model cities Herrenberg, Ludwigsburg and Osnabrück.

Model city	Measurement periods	Participants	Tracks	Detected Moments of Stress (MOS)
Herrenberg	10/2022	16	106	515.433
Ludwigsburg	07/2022 05/2023	11	114	8984
Osnabrück	09/2022 03–04/2023 09–11/2023	116	2.031	44.964

2.5. Previous research on cycling and stress

From a methodological perspective, few researchers have incorporated biostatistical data and personality-related variables into stress measurement in cycling contexts (see Table 2).

Although research suggests that negative arousal or situational stress is prevalent in cyclists' travel experiences (Caviedes & Figliozzi, 2018), cycling experiences remain underrepresented in stress research.

Besides stress, negative emotions such as anger play a role, with personal dispositions modulating such emotions (Oehl et al., 2019). These mechanisms exist for other traffic participants as well, including car drivers (Pesle et al., 2018), traffic workers (Marois et al., 2018), and commuters (Fenerich et al., 2024).

While these findings suggest a potential role of physiological stress responses in cycling as reactions to external stimuli (e.g., infrastructural barriers, conflicts with other traffic participants), little is known about the association between these responses and personality, as well as cycling-related traits. Furthermore, most studies haven't investigated stress reactions in naturalistic settings under everyday conditions.

Our study aims to fill these gaps by investigating the factors that drive physiological stress responses during everyday cycling, combining biostatistical measurements with personality assessments.

3. Research hypotheses

Based on the theoretical framework and previous research, we formulated the following hypotheses:

H1: The category "interested but concerned" cyclist exhibits increased MOS among cyclists.

H2: Psychological factors such as personality traits, locus of control, or risk affinity affect MOS in different modes.

H3: Male cyclists tend to show a lower level of MOS than cyclists of other genders.

H4: Increasing age exerts an amplifying effect on the MOS.

4. Research methodology

4.1. Study design and setting

The data encompasses three German model cities—Herrenberg, Ludwigsburg, and Osnabrück—collected from 143 participants over a period from fall 2022 to spring 2024. This extended timeframe ensures a comprehensive analysis across all seasonal variations. Recruitment was conducted through various channels, including LinkedIn, university mailing lists, local press, the German Cyclists' Association (ADFC), and church associations. Efforts were made to ensure a balanced sample in terms of age and gender.

Participants were provided with sensors for two weeks to record their ordinary cycling trips and track their MOS with the help of the provided sensors. At the start of the experiment, participants received a briefing on how the sensors and data collection process worked.

4.2. Data collection

4.2.1. Physiological measurements

The study recorded participants' physiological reactions using the EmoCycling method with empatica E4 wristbands capturing skin conductance (EDA) and skin temperature (ST) data. The data collection involved processing smartphone-based GNSS data from the E-Diary app, which integrated cycle routes into the participants' everyday lives.

The algorithm by Kyriakou et al. (2019) provided information about the geo-localization of calculated Moments of Stress (MOS) based on ST and EDA data.

The data used in the paper on cycle paths travelled and the associated detected points of increased negative attention were generated in various research projects in the context of subjective safety and cycling. Starting with the basic project 'Cape Reviso' (Zeile et al. 2024), in which the test environment consisting of biophysiological measurement and questionnaire could be tested for the first time in a cooperation of local stakeholders and ADFC in Herrenberg. From the project ESSEM two more model cities Ludwigsburg and Osnabrück, were integrated (Haug et al. 2023). The model cities were selected on the basis of their size, modal split and willingness to transform into more bicycle-friendly cities. Furthermore, the urban planning offices, local transport planning and the mayoral level

Table 4
Descriptions of the independent and dependent variables.

Dependent variable	Type	Description	Reference
High number of MOS	dich.	0: Low number of MOS* 1: High number of MOS*	Zeile et al. 2023
Independent variables			
Age (≥50 years)	dich.	0: Young (younger than 50) 1: Old (50 years and older)	
Academic degree	dich.	0: No academic degree 1: Academic degree	
Male low risk	dich.	0: Other 1: Male low risk	
Types of Cyclists			
Interested but Concerned Cyclists	dich.	0: Other types of cyclists 1: Interested but concerned	Geller, 2009
Locus of Control			
External locus of control	dich.	0: Internal locus of control* 1: External locus of control*	Kovaleva et al., 2012
Internal locus of control	dich.	0: External locus of control* 1: Internal locus of control*	
Psychological Characteristics			
Extraversion	dich.	0: Low extraversion* 1: High extraversion*	Rammstedt et al., 2012
Openness	dich.	0: Low openness* 1: High openness*	
Agreeableness	dich.	0: Low agreeableness* 1: High agreeableness*	
Conscientiousness	dich.	0: Low conscientiousness* 1: High conscientiousness*	
Neuroticism	dich.	0: Low neuroticism* 1: High neuroticism*	
Electric bicycle drive	dich.	0: Manual bicycle drive 1: Electric bicycle drive	Nobis & Kuhnimhof, 2019
Accident involvement	dich.	0: No accident involvement 1: Accident involvement	

Note. dich. = dichotomous. *based on median split.

(mayor of Herrenberg and city council member for construction in Osnabrück) were actively involved in project acquisition and processing. Table 3 gives an overview of the physiological measurements in the three model cities Herrenberg, Ludwigsburg and Osnabrück.

The measurement requirement for the cyclists was that they should measure their everyday cycling journeys, including leisure journeys, over a period of two weeks.

4.2.2. *Questionnaire*

To assess endogenous factors, a standardised questionnaire was developed to collect a) personal characteristics and sociodemographic background, b) cycling mobility patterns, c) cycling behaviour typology, and d) psychological characteristics. The study employed validated scales from Germany's Mobility Study (2017) described in Nobis & Kuhnimhof (2019), and the Leibniz Institute for Social Sciences (GESIS) (Personality measures (BMVI): (Rammstedt et al., 2012), Locus of Control: (Kovaleva et al., 2012), Risk Propensity: (Beierlein et al., 2014).

4.2.3. *Data integration*

An individual pseudonym matches the 'stress' data with the questionnaire data to evaluate the relationship between physiological stress (as measured by MOS) and personal characteristics. During the matching of the different data sources, some observations had to be excluded because, in some cases, the recording of MOS-relevant biosignals was not successful or the pseudonym could not be unambiguously assigned. The combined dataset serves as the final data source for the following statistical analyses, which include descriptive analysis followed by stepwise logistic regression. Binary logistic regression was chosen as the analysis method, as the dichotomization ensures a higher number of observations per variable category of the dependent variable and by that increases the statistical reliability (e.g. by avoiding issues related to heteroskedasticity) and interpretability of the analysis results. As the aim of the present study was to identify first tendencies and relationships, the binary representation of the number of MOS suffices the aim of the study. Same applies to the dichotomous representation of the independent variables. The number of MOS includes the detected MOS during the whole timespan of the data collection periods during the Cape Reviso and ESSEM project per participant. As the aim of the study was the investigation of the relationship between endogenous traits and characteristics of the participants and the measured MOS, the independent variables mainly include central individual characteristics related to personality and sociodemographics of the participants. Due to the fairly low number of observations, additional, non-endogenous contextual information, such as seasonal differences in data collection, were omitted in order to ensure model stability and reliability of the analysis results.

Table 5
Model 1 of logistic regression analysis.

	BIC				−2LL	Nagelkerke R^2	χ^2
	116					0.16	13.02
	β	SE	Wald	significance	Odds ratio	95 % CI for Odds ratio	
Variables						lower	upper
Constant	−0.81	0.52	2.46	0.117	0.44	−1.83	0.20
Age (≥50 years)	1.26	0.49	6.56	0.010	3.54	0.30	2.23
Academic degree	0.61	0.55	1.23	0.268	1.83	−0.47	1.68
Male low risk	−0.95	0.57	2.77	0.096	0.39	−2.06	0.17

4.3. Variables and measures

Table 4 provides an overview of the variables used for the analysis.

4.3.1. Sample Description

The sample data show an even gender distribution, with 46.7 % of participants being male, 51.1 % female, and 1.1 % identifying as diverse.[2] The average age of participants is M = 47.58 years, indicating a slightly higher age than the average age of the German population (M = 44.6 years). The sample is dominated by a high proportion of individuals with a university or university of applied sciences degree, at 65.6 %, which is higher than the nationwide reference value of 18.5 % (Research Data Centres of the Statistical Offices of the Federation and the Federal States, 2022). Further, the data suggests a diverse response in cycling types with the distribution differing remarkably from the Geller (2009) reference: 0 % in the “no way, no how” category (33 % according to Geller (2009)), 26.7 % in the “interested but concerned” group (60 % according to Geller (2009)), 64.4 % in the “enthused and confident” segment (7 % according to Geller (2009)), and 6.7 % in the “strong and fearless” category (0.5 % according to Geller (2009)). Studying the psychological constructs in the sample, we find minimal deviation from the reference value of M = 4.02 on a five-point scale (Kovaleva et al., 2012) for the Internal Control (IC) variable, with a median of M = 4.00. In contrast, the median for External Locus of Control in the sample is M = 2.00, approximately M = 0.5 points below the reference value of M = 2.52. The distribution of the Big Five variables in our sample largely corresponds to the reference values reported by Rammstedt et al. (2012). Only the openness with a median of M = 4.00 shows a more significant difference from the reference value (M = 3.41) by Rammstedt et al. (2012).

4.3.2. Data Preparation and quality assessment

The dataset was cleaned and processed for further analysis. Following a visual and analytical outlier analysis using Cook’s distance, two participants were excluded from the analysis, resulting in a final sample of 90 observations. The number of MOS as the dependent variable was standardised by dividing the number of MOS by the kilometres driven by each participant. This data was then dichotomized via a median split, creating a binary variable with above-median values coded as high number of MOS and below-median values as low number of MOS.

Alternative approaches for identifying threshold values, including the Gaussian mixed model and k-means clustering, were tested but not applied. Continuous independent variables were also dichotomized using a median split, and nominal variables, such as education level, were dummy-coded (e.g. academic degree).

The data was tested for fulfilment of the general quality criteria related to logistic regression analysis. Visual checks for autocorrelation of errors were performed, and variables were integrated stepwise by forward selection to detect potential distortions of p-values and coefficients (see Table 5 for the final model and included variables). During the blockwise model integration process, partly highly varying beta coefficients and p-values were observed, indicating instability in the formulated model. Forward selection of variables identified the gender dummy (male), risk affinity (high), and age (≥50 years) being somewhat associated. Regressing risk affinity (high) against gender (male) and age (≥50 years) showed that both variables are significantly associated with risk affinity (Nagelkerke $R^2 = 0.14$):

- Age (≥50 years) was negatively associated with risk affinity ($B = -0.04$, $SE = 0.02$, $Wald = 4.59$, $p < 0.05$; $OR = 0.96$, 95 % CI [-0.07, 0.00])
- Gender (male) was positively associated with risk affinity ($B = 1.03$, $SE = 0.48$, $Wald = 4.63$, $p < 0.05$; $OR = 2.79$, 95 % CI [0.09, 1.96])

Therefore, gender (male) was recoded by adding low-risk affinity as a condition into the gender variable. This adaptation removed the observed instability of coefficients and p-values. Subsequent blockwise model integration demonstrated the stability of the beta coefficients and p-values across all models. Before creating a combined variable, testing for significant correlations and interaction effects between the variables did not yield statistically significant results. The lack of statistically significant interactions between the analysed variables might be due to the low sample size and the naturalistic setting in which data was collected, which generally decreases statistical power and thus makes it harder to detect distinct effects. Combining gender and risk-affinity into one variable still

[2] Percentages in this section might not sum up to 100% due to non-response.

Table 6
Overview of hypotheses testing results.

Hypothesis		Result
H1	*The category "interested but concerned" cyclist exhibits increased MOS among cyclists.*	Rejected
H2	*Psychological factors such as personality traits, locus of control, or risk affinity affect MOS in different modes.*	Partially rejected
H3	*Male cyclists tend to show a lower level of MOS than cyclists of other genders.*	Rejected
H4	*Increasing age exerts an amplifying effect on the MOS.*	Not rejected

seems reasonable from a conceptual perspective, as research has shown that gender, risk affinity and age are associated (Useche et al., 2018). To determine the most suitable model for analysis, the Bayesian Information Criterion (BIC) was evaluated, as it aligns more closely with our research approach than the Akaike Information Criterion (AIC). Given the constraint of a small sample size, there was a deliberate aspiration to identify a less complex yet stable model. The model with only the sociodemographic block was identified as the most suitable for further analysis in terms of model fit and parameter count (see equation 1.; for the other models, see tables A.1–A.3).

Equation 1.

$$BIC_{constant+socio.} = 116 < BIC_{constant+socio.+cyclingtype} = 118 <$$

$$BIC_{constant+socio.+cyclingtype+psych.} = 135 < BIC_{constant+socio.+cyclingtype+psych.+cycling-relatedfactors} = 137$$

5. Results

Statistical analysis via logistic regression analysis (Table 5) including only the sociodemographic variable block yields (equation 3), based on the general form of the probability to obtain Y = 1 (equation 2),

Equation 2.

$$P(Y=1) = \frac{1}{1+e^{b_0+b_1x_1+b_2x_2+\ldots+b_ix_i}}$$

that the probability of exhibiting a high number of MOS (Y = 1) is given by

Equation 3.

$$P(Y=1) = \frac{1}{1+e^{(-0.81)_{constant}+1.26x_{age}+0.61x_{academic}+(-0.95)x_{male,lowrisk}}}$$

The results of the logistic regression (see Table 5) indicate that age ($\geq$ 50 years) has a significant impact on the probability of experiencing a high number of MOS. With a Nagelkerke R^2 value of 0.16, the chosen model explained 16 % of the variance in the existence of a high number of MOS. Being aged 50 years or older, the odds of having experienced a high number of MOS is by 3.08 times higher, compared to when being aged below 50 years (B = 1.26, SE = 0.49, Wald = 6.56, $p < 0.05$; OR = 3.54, 95 % CI [0.30, 2.23].

Besides that, no other variable in the model has been shown to have a significant impact on the probability of experiencing a high number of MOS. In addition, as shown previously in section 3.3.2., the structure of the data suggests that risk affinity, gender, and age are somehow associated. As the other considered models, including variables that address the formulated hypotheses, did not show a significant impact on the probability of experiencing a high number of MOS, based on the present data, age is the only significant predictor of a high number of MOS. Thus, H4 cannot be rejected based on the present study (see Table 6).

6. Discussion of results

This study investigated factors influencing cyclists' perceived safety by measuring physiological stress responses during real-world cycling activities across three German cities. Using the EmoCycling methodology, we collected data from 90 participants who wore physiological sensors for two weeks while cycling their regular routes. The study examined relationships between 'Moments of Stress' (MOS) and three key factor categories: Geller's cyclist typology, psychological personality traits (Big Five, locus of control, risk affinity), and sociodemographic characteristics.

Our primary finding was that age emerged as the sole significant predictor of elevated physiological stress responses while cycling. Participants aged 50 years or older demonstrated 3.54 times higher odds of experiencing heightened stress compared to younger cyclists ($p < 0.05$). Contrary to our hypotheses, cyclist typology, personality traits, and gender variables did not yield statistically significant associations with stress levels.

6.1. Interpretation of findings

The predominant role of age in predicting physiological stress responses aligns with existing literature suggesting that advanced age correlates with increased stress susceptibility in traffic environments (Ausserer et al., 2013; Schoon, 2010). This finding suggests that age-related factors—potentially including decreased physical capabilities, longer reaction times, reduced confidence, or heightened risk perception—may override other individual characteristics in determining stress responses during cycling activities.

The absence of significant effects for other hypothesized factors warrants careful interpretation. Stress, as a subjective construct, involves complex appraisal processes where the same objective situation can elicit vastly different responses depending on individual perception and coping mechanisms. During cycling, stress can be triggered by various external factors (construction sites, narrow lanes, heavy traffic) and situational elements that are inherently difficult to quantify and control in naturalistic study settings. The relationship between psychological traits and stress responses may be more nuanced than captured by our binary classification approach.

Unaccounted personality traits or variables might explain the variations observed in the MOS that were not captured in our statistical model, as suggested by current scholarly results (Varet et al., 2025). Research on cyclists' behaviour has primarily focused on the Big Five Model (Useche, 2025), as it offers the advantage of being a widely validated model applied in various contexts. However, it must be acknowledged that the Big Five Model may not capture all cycling-relevant personality traits in their entirety. Research suggests that factors such as sensation seeking, risk-taking or risk affinity, trait impulsiveness, and other personality traits are associated with cycling behavior and perception (Lim et al., 2023; Varet et al., 2025).

Our finding that gender did not significantly predict stress responses contradicts some previous research but may reflect the complex interplay between gender, risk affinity, and age that we observed in our data. The recording of gender variables to account for risk affinity suggests these factors are interconnected in ways that require more sophisticated analytical approaches to disentangle. As the present results suggest an association between gender, risk affinity, and age, this relationship merits further investigation. In the mobility context, research results show that male traffic participants with lower ages had a higher probability of engaging in risky behaviours (Useche et al., 2018b).

6.2. Methodological considerations and study design Rationale

Several methodological choices and limitations influenced our findings, which we address here with explanations of our study design decisions.

Sample characteristics and recruitment strategy: Our sample exhibited relative homogeneity, particularly in educational attainment (65.6 % university degree holders) and cycling experience (64.4 % "enthusiastic and confident" cyclists versus Geller's reference of 7 %). This homogeneity resulted from our recruitment strategy through university networks, cycling associations (ADFC), and professional networks, which naturally attracted more educated and cycling-experienced participants. While this limits generalizability, it provided a relatively controlled population for this exploratory study examining physiological stress responses—a novel approach in cycling research that benefits from reduced confounding variables in initial investigations. Homogeneity is further reflected in the low standard deviations in personality traits, such as perceived locus of control (S.D. internal control = 0.50; S.D. external control = 0.61) and conscientiousness (S.D. conscientiousness = 0.67).

Naturalistic versus controlled conditions: We deliberately chose a naturalistic approach where participants cycled their regular routes over two weeks rather than using standardized test routes. This decision was made to capture authentic stress responses in real-world conditions, as laboratory or controlled route studies may not reflect genuine cycling experiences. However, this choice inherently reduced our ability to control for environmental variables (traffic conditions, infrastructure types, weather) that could influence stress responses, potentially masking smaller effects of individual characteristics. Based on the relatively low number of observations and heterogeneous framework conditions (e.g., different motives for cycling, varying routes, times, and traffic volumes), isolating distinct or minor effects is hardly achievable.

Binary variable approach: Our decision to dichotomize continuous variables using median splits was driven by our relatively small sample size (n = 90) and the need for statistical stability. While this approach reduces statistical power and may obscure nuanced relationships, it provided more robust group comparisons given our sample limitations. Several data points were observed to lie precisely on the median, resulting in unequal group sizes. The minimal number of items per construct also imposed limitations, as quasi-metric treatment of such scenarios can be problematic for more sophisticated analyses. Additionally, the lack of normally distributed data, which could potentially influence the interpretation of results, represents another methodological constraint.

Data quality and outlier management: The exclusion of participants due to unsuccessful biosignal recording or pseudonym matching reflects the challenges of real-world physiological data collection. Our use of Cook's distance for outlier detection and the resulting exclusion of two participants was necessary to ensure model stability, though it further reduced our already limited sample size.

6.3. Limitations and future research integration

Sample limitations and expansion needs: Future research should prioritize larger, more diverse samples to detect subtle effects that may be overshadowed in homogeneous populations. Recruitment strategies should specifically target underrepresented groups, including those with lower cycling experience, diverse educational backgrounds, and varying socioeconomic status. Future studies should adopt standardized conditions and predefined routes to provide more controlled environments, thereby better isolating distinct effects that might be overshadowed in naturalistic settings.

Methodological refinements: While the Big Five Model offers validation advantages, it might not capture all cycling-relevant personality traits. Research suggests that factors like sensation seeking, risk-taking, and trait impulsiveness are associated with cycling behaviour and perception (Varet et al., 2025; Lim et al., 2023). Although risk affinity was included in the present research, it

Table A1
Model 2 of the logistic regression analysis.

					−2LL	Nagelkerke R^2	χ^2
	BIC						
	118					0.14	10.77
	β	SE	Wald	significance	Odds ratio	95 % CI for Odds ratio lower	upper
Constant	−0.65	0.55	1.39	0.239	0.52	−1.74	0.43
Age (≥ 50 years)	1.16	0.50	5.44	0.020	3.19	0.18	2.14
Academic Degree	0.54	0.55	0.97	0.325	1.72	−0.54	1.62
Male low risk	−0.89	0.57	2.48	0.115	0.41	−2.01	0.22
Interested but concerned	−0.39	0.54	0.52	0.472	0.68	−1.46	0.67

was only measured using a single-item scale. Further expanding the understanding of the relationship between personality traits and the number of MOS, including a more diverse item battery related to cycling behaviours, might increase the explanatory power of the results (e.g., Useche et al., 2018a). Therefore, future research could focus on incorporating additional psychological trait variables, such as sensation seeking, to gain a deeper understanding of the relationship between MOS and psychological traits.

Gender, risk affinity, and age relationship investigation: As our results indicate associations between these factors that require further investigation, future research should investigate this relationship more thoroughly. Research shows that male traffic participants with lower age have a higher probability of engaging in risky behaviours (Useche et al., 2018b). The present results offer some indication of potential relationships that require dedicated investigation using larger samples and interaction analysis.

Experimental design considerations: Future research should consider hybrid approaches combining naturalistic data collection with standardized route segments to balance ecological validity with experimental control. Seasonal variations, which we omitted to maintain model stability, should be systematically examined. Advanced analytical techniques, including multilevel modeling and machine learning approaches, may better capture the complex interactions between individual and environmental factors.

Technological and analytical advances: Improvements in wearable sensor technology and algorithm development may provide more precise stress detection. The integration of contextual data (real-time traffic conditions, weather, infrastructure quality) through IoT and GPS technologies could help disentangle individual from environmental factors influencing stress responses.

7. Implications and conclusions

This exploratory study provides initial evidence that physiological stress measurement can contribute to understanding cyclist vulnerability, with age emerging as a critical factor requiring attention in cycling infrastructure planning and safety interventions. The predominance of age effects suggests that cycling promotion strategies should particularly address the needs and concerns of older adults, potentially through improved infrastructure design, targeted training programs, or technology-assisted cycling solutions.

Stress, as a subjective construct, is challenging to measure and comprehend. Stress as a stimulus can even result in positive emotions following stimulus appraisal and can affect biophysical responses in various ways. As the nature of the resulting emotion determines whether individuals engage in or avoid specific actions (Lim et al., 2023), advancing the understanding of individual predispositions and their impact on stress appraisal is crucial.

The methodological framework established here—combining physiological measurement with psychological and demographic assessment—offers a foundation for future investigations into cyclist stress experiences. While our findings are preliminary and require replication with larger, more diverse samples, they demonstrate the feasibility of objective stress measurement in real-world cycling contexts and highlight the importance of age-related factors in cycling safety research.

In conclusion, this study offers preliminary evidence on the potential for measuring physiological stress responses in cyclists and their connection to individual factors, particularly age. Despite its limitations, it provides a foundation for future research investigating the complex interplay of factors affecting cyclists' stress experiences in urban environments.

8. Glossary of key terms

Gender Mobility Gap: The disparity in mobility patterns, transportation access, and travel behaviors between genders, often reflecting broader social inequalities.

Eustress vs. Distress: Eustress refers to positive stress that motivates and improves performance, while distress refers to negative stress that can be harmful and debilitating.

Moments of Stress (MOS): Identifiable points during cycling where negative physiological arousal is detected through biosignals, indicating a stress response to environmental conditions.

EmoCycling: A mixed methods research approach that combines physiological measurements with subjective assessments to identify and analyze stress reactions while cycling.

Electrodermal Activity (EDA): Also known as Galvanic Skin Response (GSR), measures changes in the skin's electrical conductivity caused by sweat gland activity, which increases during stress responses.

Skin Temperature (ST): A physiological parameter that typically decreases during stress reactions as blood flow is redirected to muscles and vital organs.

Table A2
Model 2 of the logistic regression analysis.

	BIC				−2LL	Nagelkerke R^2	χ^2
	135					0.24	14.95
	β	SE	Wald	significance	Odds ratio	95 % CI for Odds ratio lower	upper
Constant	−1.41	1.30	1.18	0.277	0.24	−3.95	1.13
Age (≥ 50 years)	1.72	0.60	8.20	0.004	5.59	0.54	2.90
Academic Degree	0.49	0.61	0.62	0.429	1.62	−0.72	1.69
Male low risk	−0.73	0.75	0.94	0.332	0.48	−2.19	0.74
Interested but concerned	−0.14	0.66	0.05	0.827	0.87	−1.44	1.15
Locus of control (internal)	−0.73	0.76	0.91	0.340	0.48	−2.22	0.77
Locus of control (external)	0.72	0.68	1.13	0.288	2.06	−0.61	2.05
Extraversion	0.50	0.86	0.34	0.560	1.65	−1.18	2.18
Openness	−0.25	0.82	0.09	0.763	0.78	−1.84	1.35
Agreeableness	0.14	0.58	0.06	0.807	1.15	−1.00	1.29
Conscientiousness	0.70	0.60	1.38	0.240	2.02	−0.47	1.87
Neuroticism	−0.12	0.61	0.04	0.841	0.89	−1.31	1.07

Table A3
Model 4 of the logistic regression analysis.

	BIC				−2LL	Nagelkerke R^2	χ^2
	137					0.31	19.94
	β	SE	Wald	significance	Odds ratio	95 % CI for Odds ratio lower	upper
Constant	−1.66	1.43	1.36	0.244	0.19	−4.46	1.13
Age (≥ 50 years)	2.15	0.68	9.93	0.002	8.54	0.81	3.48
Academic Degree	0.27	0.65	0.18	0.675	1.31	−0.99	1.54
Male low risk	−0.18	0.79	0.05	0.820	0.84	−1.73	1.37
Interested but concerned	0.04	0.69	0.00	0.952	1.04	−1.31	1.39
Locus of control (internal)	−1.01	0.83	1.49	0.223	0.37	−2.63	0.61
Locus of control (external)	0.68	0.70	0.92	0.337	1.97	−0.70	2.06
Extraversion	1.00	0.91	1.21	0.272	2.72	−0.78	2.78
Openness	−0.31	0.86	0.13	0.715	0.73	−1.99	1.37
Agreeableness	0.22	0.62	0.13	0.722	1.25	−0.99	1.44
Conscientiousness	0.49	0.67	0.54	0.462	1.63	−0.82	1.80
Neuroticism	0.09	0.63	0.02	0.887	1.09	−1.15	1.33
Electric bicycle drive	1.06	0.67	2.51	0.113	2.89	−0.25	2.38
Accident involvement	−0.82	0.65	1.59	0.207	0.44	−2.11	0.46

Geller's four types of Cyclists

- Strong and Fearless: Cyclists with excellent bicycle control and high stress tolerance who cycle under all conditions.
- Enthusiastic and Confident: Daily cyclists with confident riding skills and medium safety needs.
- Interested but Concerned: Cyclists with safety concerns, less confident riding skills, and low stress tolerance.
- No Way, No How: Individuals who do not cycle and have poor control of bicycles with very low stress tolerance.

Big Five Personality Traits: A psychological model that categorizes personality into five dimensions: Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism.

Locus of Control: A psychological concept describing the extent to which individuals believe they have control over events in their lives:

- Internal Locus of Control: Belief that one's actions determine outcomes.
- External Locus of Control: Belief that external factors like fate or powerful others determine outcomes.

Risk Affinity/Propensity: An individual's willingness to take risks, measured in the study as a relevant factor potentially affecting stress responses during cycling.

Bayesian Information Criterion (BIC): A statistical criterion used for model selection, with lower values indicating better fit. The study used BIC to identify the most appropriate regression model.

Autonomic Nervous System (ANS): The part of the nervous system responsible for controlling involuntary physiological processes, including stress responses.

Emotion Sensing: A research approach that captures emotional states through physiological measurements, particularly useful for identifying emotional responses to urban environments.

Emotional Cartography: Concept originated by Christian Nold (2009) involving the georeferenced recording of arousal states within urban contexts, providing spatial mapping of emotional responses.

Triangulation: A research approach that combines multiple data sources, methodological approaches, and theoretical perspectives to enhance understanding and minimize blind spots, distinct from mixed methods by its focus on connecting different perspectives rather than just combining qualitative and quantitative approaches.

Transactional Stress Model: Proposed by Lazarus (1999), conceptualizes stress as emerging situationally through human-environment interactions, with emphasis on cognitive appraisal. This model has the highest complexity among stress theories but offers nuanced understanding of individual stress responses.

Logistic Regression: The statistical method used in the study to identify relationships between the number of Moments of Stress and various independent variables including sociodemographic factors, cyclist typology, and psychological traits.

Median Split: A data analysis technique used in the study to convert continuous variables into dichotomous (binary) variables by dividing the sample at the median value.

Response-based Stress Models: Theoretical frameworks (e.g., Cannon, 1932; Selye, 1956) that examine physiological responses to external stimuli, forming the foundation of psychophysiological stress research. A key limitation is their assumption of uniform stress responses across individuals.

Stress as Stimulus Model: A theoretical framework that emphasizes psychological implications of stress, positing the existence of "critical life events" (Holmes & Rahe, 1967) that objectively induce stress to varying degrees.

Funding statement

This work was completed as part of the research project *Emotion Sensing for (e-)Bicycle Safety and Mobility Comfort – ESSEM*, funded by the mFUND funding program of the German Federal Ministry for Digital and Transport [funding code: 19F2195A].

Credit authorship contribution statement

C. Schmidt-Hamburger: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Agola:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Hamel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P. Zeile:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **N. Haug:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Appendix

Data availability

The authors do not have permission to share data.

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