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Identifying urban stress and bicycle infrastructure relationships: a mixed-methods citizen-science approach

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ABSTRACT

Active mobility is considered a key aspect of the mobility revolution and is therefore elementary in combating the climate crisis. However, a lot of research is needed to improve the situation of active mobility, especially concerning inhibiting factors in the choice of active means of transport. For reasons such as the high volume and speed of motorised traffic, heavy noise, and pollution levels, urban space is often associated with increased stress. The generation and provision of stress data are therefore of particularly high importance for urban planning. The citizen-science approach of the BMDV[1]- project ESSEM implements a triangulating approach that uses biological markers and standardized questionnaires to make statements about individual 'stress'. In the future, this should help identify vulnerable groups and better address them in project development and planning. The presented study describes the use of participatory methods based on three 'stress hotspots' in Osnabrück, taking into account different forms of cycling infrastructure.

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Urban planning; cycling planning; emotion sensing; EmoCycling; Citizen science; active mobility

1. Introduction

1.1. Background

Whether commuting to work or education or traveling to leisure activities – mobility shapes our social lives and reflects our individual needs. As an alternative to private cars and a supplement to public transport and walking, cycling is becoming increasingly relevant. Due to the COVID-19 pandemic and the rising development of pedelecs, the bicycle is taking on a key role in urban mobility. Furthermore, cycling is environmentally friendly and can improve personal well-being and health. These arguments for bicycle use are still not reflected in the modal split of many cities. One reason that restricts widespread bicycle use is the limited subjective perception of safety. Factors such as travel time, costs, and mode choice also depend on the perceived safety of the mobility form. The 'National Cycling Plan 2020' also states that cyclists who feel particularly unsafe also cycle less often (BMDV, 2022). In urban planning, the difficulty in identifying stress-triggering and dangerous spatial situations, such as critical intersections and forms of guidance, often exists. While infrastructure improvements are implemented based on

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statistically relevant road crash hotspots, so-called near misses are often unrecognized in this context. This means that these events are not included in accident statistics but strongly prevent undecided cyclists from using bicycles. However, to plan ecologically, spatially, and socially sustainable and equitable cities, it is time to focus on human perception in mobility research. Especially in the field of active mobility, such as cycling, people are directly exposed to their environment. Providing data and objectifying much-discussed issues such as perceived safety is therefore essential for future decision-making at the community level (SORENSEN & MOSSELEMI, 2009).

1.2. ESSEM – details and project goals

The project ESSEM ('Emotion Sensing for (E-)Bicycle Safety and Mobility Comfort') is funded by the German Ministry of Digital Affairs and Transport (BMDV). The following paper provides a general overview of the structure and implementation of the project, the methods used, and the initial findings about various infrastructures. For detailed information on the structure of the project, refer to ZEILE et al. (2023). Further information about the applied evaluation methods and the analysis of the bicycle infrastructure is provided in the paper by SCHMIDT-HAMBURGER et al. (2023) (SCHMIDT-HAMBURGER et al., 2023; ZEILE et al., 2023).

ESSEM aims to increase the comfort and safety of cyclists and thus contribute to sustainable and climate-neutral mobility. Based on a triangulation process consisting of iterative and sensor-based surveys of environmental and biophysiological data and standardized questionnaires, the project identifies, analyses, and evaluates stress points in the local bicycle infrastructure. The cities of Ludwigsburg and Osnabrück serve as model cities for the project, with around 350 test persons participating in each during the three-year project period (ZEILE et al., 2023). According to the citizen-science approach of the project, the research data will be made available as open source at the end of the project.

1.3. Research questions

The following research questions attempt to shed more light on the issue of safety perceptions among cyclists, particularly regarding the influence of infrastructures, socio (or socio-economic) backgrounds, and how these findings can help the cycling culture in general. The example of the city of Osnabrück will be used to illustrate this.

(1) Where do cyclists feel stressed?
(2) With which different methods and settings can citizens be integrated into the measurements and analysis?
(3) To what extent do personal dispositions, such as gender, age, or personality play a role in this?
(4) To what extent can statements be made about the connection between different designs of bicycle infrastructure and stress?

1.4. Structure of the contribution

The article is divided into the following chapters:

An overview of the state of the art of research (2), divided into 'Objective and Subjective Perception of Safety' (2.1), the definition of 'types of bicycles' (2.2), an explanation of 'The Construct of Stress' (2.3) and the 'Influence of street space on the subjective perception' in 2.4, and the basics of measuring physiological parameters to detect emotions in the section 'EmoCycling' (2.5).

Chapter 3 explains the methodology of data collection using the example of Osnabrück, which is divided into the initial data collection phase (3.1), the conduct of the interviews for bicycle type definition and personal safety perception (3.2), the collection of human sensory data through EmoCycling (3.3).

Chapter 4 provides a more detailed description of the analysis methods used and the results obtained. In this context, the triangulation process used in the project (4.1), the citizen science participation formats (4.2), and the analysis of the EmoCycling measurements and infrastructure in Osnabrück (4.3) will be discussed.

The article's research concludes with a discussion of the results and an outlook on further planned steps (chapter 5). The key data of the study are summarized in chapter 6, as a conclusion.

2. State of research

2.1. Objective and subjective perception of safety

Bicycle safety consists of objective and subjective dimensions and their correlation (JOHANNSEN, 2013). Referring to this, objective safety describes a quantitative view of traffic accidents. The basis for this is the publication of police road crash reports. Subjective safety, on the other hand, is an emotional view of the threat posed by a traffic situation by the road users themselves (FULLER, 2005). Therefore, cycling experts consider the 'stress reduction' of cycling as an important factor to increase the proportion of cycling (GRAF, 2016). In everyday life, cyclists use the bicycle as their primary means of transportation only if they feel safe while cycling. This fact has a significant impact on people who are non-users or occasional users of bicycles. Individual mobility behaviour thus depends not only on infrastructural or interactive factors ('exogenous') The effect of exogenous influencing factors also varies depending on personal, characteristics ('endogenous'). These include gender, age, mobility profile (people with or without disabilities), trip purposes, habits, and psychological dispositions (SCHMIDT-HAMBURGER, 2022).

2.2. Classification into cycling types

For a better classification of the participating cyclists, we adopted the taxonomy of GELLER (2009) and modified it slightly (Table 1).

Besides a biopsychological point of view, there are indications that genetic or psychological predispositions can strengthen or mitigate stress reactions. Depending on their predisposition, experience, or access to other modes of transport, cyclists therefore assess situations quite differently (PASCHALIDIS et al., 2016). Personality, control beliefs, and risk tolerance are particularly important in this context (KOVALEVA et al., 2012; SCHANDRY, 2016). These data are collected utilizing standardized questionnaires before the sensor measurements and the results are included in the evaluation. It is

Table 1. Types of cyclists (own presentation based on GELLER, 2009.).

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, • confident, medium safety needs	• No everyday cycling • Safety concerns • open-minded toward bicycles	• 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

Table 2. Descriptive analysis of the sample. (own calculation).

Variable	Description	$N_{participants}$=26 (in %)	N_{MOS}= 11996 (in %)
F1a	Age (>45)	54	61
F1b	Gender (female)	46	46
F1c	Education, high	42	
Cyclist	Cycling types	0	0
	No chance no matter what	27	22
	Interested cyclists	70	68
	Everyday cyclists	3	10
	The strong and fearless cyclists		
Drive Type	Type of drive of the bike	60	
	Conventional	40	
	electronic		
Bike Type	Most commonly used	42	
	Trekking bike	31	
	City bike		
Situation	Evaluation of the situation for cyclists in Osnabrück	0	
	very good, good	12	
	satisfactory	42	
	sufficient	31	
	poor	15	
	insufficient		
F4a	Big Five personality traits	54	52
	Extraversion (above average)	69	75
	Neuroticism (above average)	65	68
	Openness (above average)	73	77
	Conscientiousness (below average)	58	59
	Agreeableness (below average)		
F4b	Conviction of Control	62	54
	Internal (below average)	81	54
	External (below average)		
F4c	Risk affine	62	59
	Statistical key figures = 461 MOS; = 443 MOS;		

hoped that this will identify particularly vulnerable groups in terms of stress to gain knowledge about barriers to equality for cyclists. Further insights can be gained from the increase in cycling behaviour. According to GELLER (2009), cyclists can be divided into four groups: 'the strong and fearless', 'the enthusiastic and confident', 'the interested but concerned' and 'no chance, no matter what' (GELLER, 2009). An overview of the characteristics is given in Table 1. In this context, it is important to highlight that the transitions between the groups should be viewed dynamically. Concerning cycling promotion, it is interesting in projects such as ESSEM to focus especially on the stressful experience of the 'interested but concerned'.

2.3. The construct of stress

Urban space is often associated with increased stress and an excess of stress-related illnesses such as depression, cardiovascular disease, and schizophrenia (ADLI, 2017). To minimize these serious consequences in planning efforts, it is important to provide a better understanding of stress research. Stress theories differ in terms of adaptability and operationalizability. Stress always arises when, depending on the theoretical underpinning, the physique (stress-as-a-reaction) or psyche (stress-as-a-stimulus or stress-as-a-transaction) must muster resources to process environmental stimuli. The most prominent stress model, on the one hand, is the stress model according to LAZARUS (1999). At the same time, however, it is also the most complex one, since stress always arises situationally in the interaction of people and the environment. On the other hand, there are stress-as-a-reaction models (CANNON, 1932; SELYE, 1956), which examine the physical reactions to an external stimulus (BERCHT, 2013). Critical here is the assumption that a stimulus 'stresses' all people equally (LYON, 2005). The third group of theories, which understand stress as a stimulus, focuses on the psychological effects. In this context, it is assumed that there are 'critical life events' (HOLMES & RAHE, 1967) that objectively trigger stress to some extent. Due to developments in emotion research in this field, the stress-theoretical basis of this paper is more in line with models from the stress-as-a-reaction perspective. Nevertheless, subjective components are included in the data collection and analysis.

2.4. Influence of street space on subjective perception

Regarding the relationship between stress and infrastructure, it is obvious that safe infrastructure can be named as one key contributor to the promotion of bike traffic in cities (DIGIOIA et al., 2017; REYNOLDS et al., 2009). In this context, different design solutions are discussed controversially in the light of conflicts in the use of street space, and space restrictions but also about safe and qualitative bike infrastructure (AUTELITANO & GIULIANI, 2021; HULL & O'HOLLERAN, 2014; VAN PETEGEM et al., 2021). Therefore, traffic engineering was mostly focused on objective traffic safety, focusing solution findings for certain street designs on the analysis of accident statistics and fluidity of motorized traffic. A more comprehensive evaluation of safe mobility infrastructure and in particular bike infrastructure today discusses the aspect of subjective safety in addition to quantifiable objective traffic data (Götschi et al., 2018). Subjective safety among other aspects looks at how street users feel in certain contexts, or if they are overwhelmed by other road users, like cars. Multiple studies show the extent of research and debate on the topic (ALDRED & GOODMAN, 2018; BECK et al., 2021; NILSEN, 2004; VON Stülpnagel & Binnig, 2022). All in all, the subject considers the sense of security and besides positive perceptions like comfort, or well-being, the feeling of previous stress.

Nowadays the aspect of subjective safety, or rather safe and comfortable design solutions finds recognition in more and more design manuals of bike infrastructure. In this context, especially the Dutch 'Crow Manual', considers more vulnerable groups of cyclists like children or elderly people (RIK DE GROOT, 2016). In Germany, the FGSV (Forschungsgesellschaft für Strassen- und Verkehrswege) addresses the topic of subjective safety, though it can be argued that it's still not implemented in the design solutions of its manual for bike infrastructure the ERA (Empfehlung für Radverkehrsanlagen) or it's manual for city streets, the RAST (in German: Richtlinien für die Anlage von Stadtstraßen/'Guidelines for the construction of urban roads'). This shows that data and an extensive analysis of the stress experienced on certain cycleways, or rather certain street design solutions are still missing. This data and the aspect of subjective safety should be evenly balanced with other data like accident statistics, or, for example, the capacity of street design and intersections for all street users. In this regard, the concerns of pedestrians and other social uses of urban streets besides mobility have to be highlighted (GEHL, 2015).

2.5. Detection of stress – during cycling

The procedure of recording biostatistical data in a georeferenced manner and following the visualization in maps goes back to Christian NOLD (2009). His 'emotional cartography' (NOLD, 2009) allowed humans and their physiological responses to serve as a kind of sensor for the first time, recording the state of stress or arousal in an urban context.

A good overview of the topic of both 'stress while cycling' and general approaches to measuring stress can be found in TEIXEIRA et al. (2020). Exemplary here are the works from OKEN et al. (2015) as well as ZHANG et al. (2016) mention factors from psychological and sociological such as the 'internal and external environment', disturbances, future expectations, negative neighbourhood characteristics, or social threats.

In contrast, MEKURIA et al. (2012) attempted to determine a potential stress level for cycling in different road sections based on attributes of the infrastructure.

The relationship between bicycle commuting and stress in adults, however, has been investigated by only a few studies (f.e. AVILA-PALENCIA et al., 2017; KAPLAN & PRATO, 2016). The same applies to the relationship between environmental factors and stress by measuring physiological signals (FITCH et al., 2017; KYRIAKOU & RESCH, 2019). The following approaches use psychophysiological data to generate stress biomarkers during cycling (CAVIEDES et al., 2017; FITCH et al., 2017; ZEILE et al., 2016; WERNER, 2019). It was during this time that the concept of 'EmoCycling' (ZEILE et al., 2016), which originated in the Urban Emotions Initiative, emerged and became more 'mass-market' and weather-independent in technology through further developments by KYRIAKOU et al. (2019) and the more recent adaptation by MOSER et al. (2023) using the Empatica E4.

The assessment of stress-inducing causes during cycling by comparing co-occurring video recordings, interviews, and stress triggers was carried out by Groß et al. (2016) and MERK et al. (2021). In conjunction with the study 'Safety and Usability of Marked Cycling Routes' (RICHTER et al., 2019), it was thus possible to compare the main causes of stress on cycle protection lanes, in mixed traffic as well as on protected cycling facilities.

Now it is possible to measure stress in the form of reactions although it is obvious that theoretical limitations must be accepted. In general, the EmoCycling method uses biological indicators to identify Moments of Stress (MOS). That is because the human organism when confronted with a stressor, regulates endogenous stress responses to establish homeostasis. These responses are detectable through a variety of body-related parameters and are recognized as a proven method for measuring stress from external stressors. These include an increase in electrodermal activity (EDA) and a decrease in skin temperature (KYRIAKOU & RESCH, 2019; SCHANDRY, 2016). Based on the functioning of these biosignals, KYRIAKOU et al. (2019) developed an algorithm that can detect people's MOS using wearable biosensors Empatica E4.

The data is collected in an app ('e-diary') on a smartphone. The result is a database in which one line corresponds to one second of the measurement period and provides information about a MOS (yes/no) and its geographic coordinates, which can thus be read and visualized in a geographic information system (GIS).

2.6. Citizen science

STRASSER et al. (2019) provide a relevant definition of Citizens Science (CS): 'Citizen Science' offers to turn anyone into a scientist, promising to produce new knowledge, educating the public, and above all reconfiguring science from a closed to an open activity. In short, 'democratizing' science (STRASSER et al., 2019). This approach allows more sustainability in the context of research efforts and support from civil society and a redistribution of power. The relevance of collaboration between researchers and civil society, but also NGOs or governments, is also reflected in the Sustainable Development Goals of the United Nations and is thus widely recognized (SHERBININ et al., 2021).

The practice of Citizen Science follows a long tradition but was not a subject of scientific elaboration until the 1990s. The participation of different actors in knowledge generation has been increasing for several years. Important reasons are the integration of the social context of research, but also the development of information and communication technologies, such as smartphones and social media. These simplify collaboration and data collection (TROJAN et al., 2019).

In the literature, there are various attempts to typologise CS projects to identify their degree of participation and to capture knowledge about the diversity of participatory practices. These were first classified by François Grey, who calls 'volunteer thinking', 'volunteer sensing', and 'volunteer computing' (GREY, 2012). Strasser et al. added "sensing, computing, analyzing, self-reporting, making to capture the greater practices of CS to this canon. Depending on the nature of the project, the different forms lend themselves, or mixed forms are not uncommon (STRASSER et al., 2019). CS can be realized by the identification of research questions, data collection, interpretation, and evaluation within research projects. Critical is naturally the commitment of the participants, the development of a common understanding, especially when participants from different areas such as civil society, community, and research collaborate, and different rationalities and interests can compete (STRASSER et al., 2019).

Critics inside often cite lower-quality data (SHERBININ et al., 2021). There are also concerns about control and platform domination by larger technology companies (TROJAN et al., 2019). The associated decentralized storage of data and, if necessary, collaboration with external companies also bring data protection aspects and ownership issues to the fore. According to STRASSER et al. (2019), CS lends itself when the focus is on experimental or embodied knowledge. Here, reference is also made to the consequences of the dominating epistemology of science. Furthermore, the use of CS can also serve to pacify the social order or the pacification of social conflicts. Another relevant question is the remuneration of volunteers, be it financial or otherwise. There is also criticism of the devaluation of trained researchers. Could the widespread use of CS lead to an 'Uberization' (STRASSER et al., 2019) of the science sector and consequently depress wages.

However, Citizen Science is also about increasing the validity of results, as the knowledge generated is not only curated by researchers but 'new interoperable representations of knowledge' (ALBAGLI et al., 2015). Concerning research efforts around the built environment, Citizen Science thus has an important role to play, as the object of research is people and their concrete living environment.

In ESSEM, a broader understanding of Citizen Science is used. Through the multi-stage procedure with pure tracking by the Bike Citizens App in the initial phase, citizens were able to actively involve themselves in a – pre-structured – framework already in the measurement phases by freely answering the questionnaires and freely choosing the routes. In contrast to the approach that Citizens Science develops unprompted from the citizenry, here the citizens are involved in the measurements in iterative loops, where the setting can be improved, and also the citizen knowledge about specific problem points is collected. In addition, these insights will be used to work with citizens to develop a route that targets both personal potential stress points and stress points of interest for the general public. We are moving here between participation in experiments, providing local knowledge, and participation as preparation for rebuilding processes of the cycling infrastructure.

3. Data collection phases

The majority approaches of former projects used the Body Monitor Smartband (ENGELNIEDERHAMMER et al., 2019), Galvanic Skin Response (GSR) (BIRENBOIM et al., 2019; OSBORNE & JONES, 2017; SHOVAL et al., 2018), or other variables such as Heart Rate Variability (I Agustí et al., 2019) in the context of their measurement setting. Even if ESSEM's setting is based on similar parameters, in contrast, the presented citizen-science approach allows an independent implementation of the measurement routine by the test persons (ZEILE et al., 2023).

3.1. Phase 1: initial data collection

The initial data collection of the project includes the acquisition of participants by project partner Bike Citizens (BIKE CITIZENS GmbH, 2023) via their same-named application 'Bike Citizens'. The Bike Citizens Analytics tool 'BCA' (CYCLINGDATA, 2023) was then used to analyze the data collected. According to ESSEM's citizen-science approach (cf.

Chapter 2.6), the goal of the initial data collection was to make participation as pleasant and easy as possible for the test persons to reach as many participants as possible.

First, a link to the ESSEM website provides further information on the data collection. As soon as users agree to participate in the initial data collection via the Bike Citizens App (Figure 1), the application records routes used by approximately 350 subjects. Participants collected data daily during a determined period. The analysis of the anonymized datasets happens in the last step and maps a combined graphic showing the main infrastructure networks and the frequency of bicycle use. Data from the initial data collection phase then forms the basis for the multi-phase EmoCycling measurements carried out during the summer of 2022.

3.1.1. Results of initial data collection in Osnabrück

The BCA analysis portal then collects the user data and calculates various bike-specific conclusions based on the trajectories. For example, it is possible to determine the intensity concerning the number of cyclists in the network to show the average speed per road segment. In addition, another feature is to identify (forced) waiting zones about their frequency, determine the action radius of the participants, and calculate the attractiveness of the road segment compared to the whole network. The attractiveness function identifies cyclists' preferred and avoided paths: If the segments are displayed in red, cyclists take a detour and avoid the shortest route. In contrast, popular road segments appear in green. The line thickness indicates the intensity.

Figure 2 shows the results of this analysis in Osnabrück, referring to ZEILE et al. (2023). In Osnabrück, the intensive use of paths in the city center is a special characteristic. The western areas (especially Katharinenstraße, which is designated as a bicycle lane), as well as the 30 km/h zones in the Wüste district, have a high level of bicycle use.

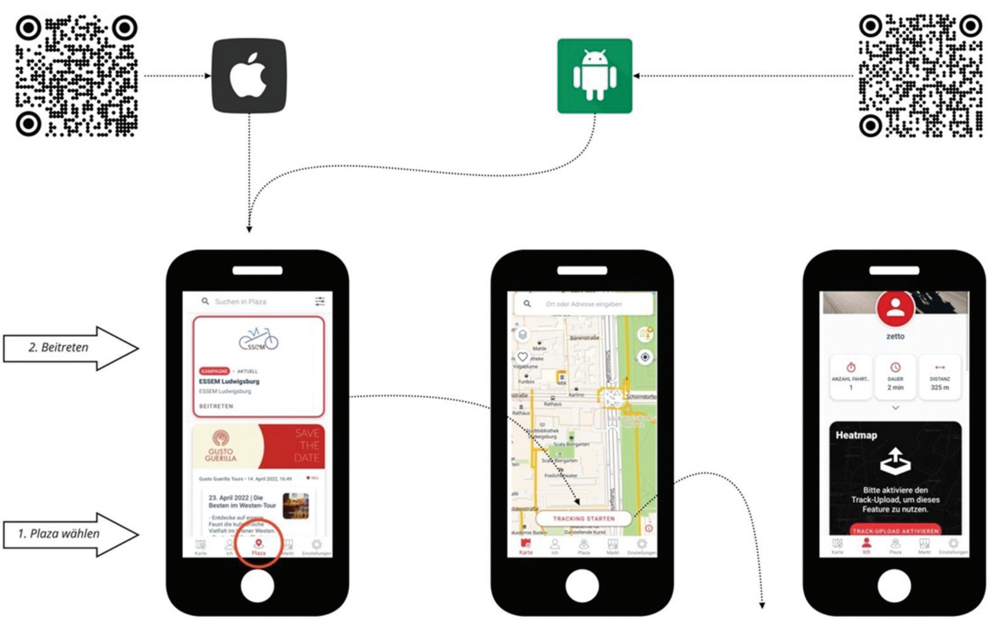

Figure 1. Setting and flow of the initial data collection: bike citizens app. (own figure).

Figure 2. Initial data collection in Osnabrück: main route network (left) and attractions (right). (own figure based on bike Citizens Analytics and OpenStreetMap).

In contrast, many cyclists avoid Martinistraße, which runs parallel to Katharinenstraße in the south with a strong MPT dominance, and Lotter Straße in the north.

Also, the southwestern inner city ring road is avoided by cyclists. In the south in Kalkhügel, Sutthauser Straße is bypassed in favour of Burenkamp. In the southeast, the participating cyclists prefer Meller Straße to the four-lane Hannoversche Straße.

3.2. Interview process and subject selection phase 2

In addition, a standardized questionnaire based on validated scales of mobility in Germany (2019) from the BMDV (NOBIS, 2018), Leibniz Institute for Social Sciences (GESIS), and Geller's (2009) types of cyclists was developed to supplement the sensor-based data with endogenous factors. In this regard, the aim is to obtain further information about the participants that provide insight into their mobility behaviour and personal dispositions. This information supports the observations on stress perception.

Traditionally, the personality of individuals is determined based on the so-called 'Big Five', which consists of the characteristics of extraversion, neuroticism, openness, conscientiousness, and agreeableness. The Big Five are considered to have good predictive power for certain aspects of life. 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).

The survey of the ESSEM project is accessible via LimeSurvey, which ensures the quick creation of a first statistical analysis. The data is collected anonymized. Therefore, to comply with data protection regulations and to correlate data from the survey with data from the sensor-based measurement, each participant creates a pseudonym. At the same time, the survey results provide information for ensuring that the sample for the sensor-based measurements is as representative of a cross-section of the population as possible. In this way, the participants can voluntarily provide their email addresses as a contact option.

3.3. Phase 2: EmoCycling data collection

The second data collection phase was carried out in Osnabrück beginning in September 2022. At the time of publication, a population of 120 persons is planned by the end of the survey period under review. Currently evaluated and as an example for the whole method are 30 participants. For this purpose, the 30 test persons selected through the initial data collection and the standardized questionnaires were divided into two groups of 15 test persons equipped with the measuring instruments. Table 2 provides an overview of the composition of the sample. In the selection of participants, the approach of ESSEM is highly concerned with ensuring gender parity, as is reflected in the sample. The average age of the participants was 45 years. Altogether, the educational level can be classified as fairly balanced: 42% of the participants had a university degree. In terms of cycling types, there is a preponderance of everyday cyclists (70%), followed by interested cyclists. Most bicycles are powered by muscle power (60%). Overall, transportation infrastructure is rated as poor (46% find this at least poor). On average, participants were more likely to be extroverted, neurotic, and open-minded. The characteristics of conscientiousness and agreeableness were rather low. The level of the internal locus of control was more pronounced than the external locus of control. People tended to be viewed as more likely to believe that they were causally responsible for their actions rather than external forces. In addition, people are more likely to be risk averse (62%).

After adjustment, the 26 participants had a total of 11,996 Moments of Stress with an average of 461 MOS and a median of 443 MOS. Therefore, the range is from 108 to 1205.

During the collection, the physiological stress reactions of the participants are recorded, located, and mapped according to the EmoCycling method. Referring to the approach of ZEILE et al. (2023), Empatica E4 Smartbands are used to record near-body data, locate it via GPS using a smartphone, and collect them in the E-Diary app (Figure 3).

After a brief introduction, the participants of the ESSEM project could take the data collection equipment home with them and independently connect the devices before each bicycle trip. This approach promotes a high integration of the measurements in the participants' everyday life under the risk of reduced comparability of cycling volume and variations of routesData acquisition with the smartphone provides a packed Spatial-Lite database. The outcome data with the identified Moments of Stress was stored in machine-readable CSV format (KYRIAKOU & RESCH, 2019; TEIXEIRA, 2020). Further collected attributes besides geocoordinates longitude and latitude are Unix timestamp, MOS score, raw GSR and ST values, time_iso, speed, and acceleration.

4. Analysis methodologies & results

4.1. Triangulation process

To research the stress experience of cyclists, ESSEM uses a triangulating procedure between methods (FLICK, 2008). With this method, the disadvantages of one

Figure 3. Setting of the EmoCycling data collection: smartphone and Empatica E4 Smartband. (own figure).

method can be compensated for by the addition of another during data collection, analysis, and interpretation. Due to the subjectivity and complexity of the research object, a methodological procedure that reflects these circumstances is required (cf. Chapter 2.3). Figure 4 provides an overview of the methodological approach, showing that the triangulation process was used for data collection (standardized as well as open, sensor data), analysis (spatial and statistical), and interpretation.

4.2. Citizen participation formats

Across the various data collection phases, it is a particular concern of the ESSEM project and its citizen-science approach (cf. Chapter 2.6) to come into direct contact with the test persons. Various dialog formats have already been carried out or are being planned. As a final event of the EmoCycling data collection phase, a citizens' workshop was held in June 2023 in Osnabrück. The citizens' workshop served as a dialog forum and was conducted together with the test persons, representatives of the city of Osnabrück, and the project leaders. After the presentation of the results of the EmoCycling measurements in the form of the overall heat map, the neuralgic points were discussed with the test persons in small groups.

Important insights were gained and some challenges for future measurements were identified:

(1) During the discussion, it was pointed out several times that the test persons deliberately avoid stressful routes during their everyday journeys and that the

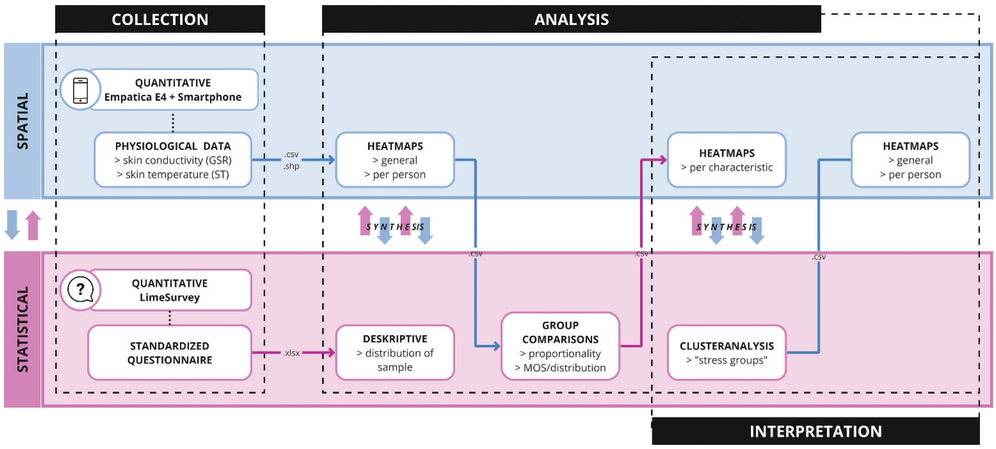

Figure 4. Scheme triangulating process. (own presentation).

measurements are thus falsified in some respects. In doing so, the subjects also accept further detours.

(2) The identified Moments of Stress accumulate in right-to-left situations. These were also subjectively perceived as disturbing by the test subjects.

(3) The stress perceived by the subjects at some of the identified points is extremely dependent on the times of day and the resulting traffic volume. At peak times, these neuralgic points were sometimes perceived as very stressful, even if they were perceived as very pleasant during the rest of the day.

4.3. Heatmap and infrastructure analysis

For a better spatial assessment, especially for citizens and decision-makers participation formats, in this approach, the identified stress points are subjected to a Kernel Density Estimation (KDE) to determine spatial clusters. In popular scientific terms, this creates heat maps of stress reactions within a city. Due to the already mentioned time delay of the stress detection of 3–5 seconds and depending on the average speed of cyclists, a radius of 30 m proved to be helpful for the KDE, as well as a colouring of the maximum value of 25 with the number of almost 46,000 determined stress points. Knowing that spatio-temporal phenomena cannot yet be taken into account here and that the individual points have to be checked again in terms of planning when taking a precise spatial view, this approach is well suited for determining focus areas and is successfully used in workshops.

In the future, a normalised stress attribute, i.e. the ratio between the number of stress moments and the number of total measured physiological values within a certain radius, will be spatially clustered in the spatial analysis (KYRIAKOU & RESCH, 2019). For this purpose, the Getis-Ord Gi* method is used, which recognises attribute clusters in geographical space. Consequently, hot spots, i.e. the clustering of stress moments, and cold spots, the clustering of 'relaxation moments', can be spatially identified and mapped.

As a result, for the investigation of bicycle-related infrastructure, we figured out that cycleways on major streets in cities with a higher amount of motorized traffic and correlations between stress levels and certain design solutions are examined. This concerns e.g. advisory bike lanes and seperated and protected bike lanes. To further examine the underlying hypothesis that protected bike lanes and distance to other road users (e.g. cars and pedestrians) are key factors, different designs of bike infrastructure in Osnabrück are superimposed with the data of the stress levels through the EmoCycling-methodology. Major urban roads are selected because here design solutions differ the most. On minor side streets designs mostly call for mixed traffic and generally speaking can only differ in ordinances like the Bicycle Streets, or more precisely the German "Fahrradstraße ". On the other hand, the cities' major arteries are mostly characterized by high traffic volumes, and high speeds and are oftentimes the most direct connection from A to B. The analysis of subjective safety, therefore, concerns that design solutions for this type of infrastructure are of great interest.

The analysis focuses on the areas in Osnabrück (Figure 5), regarding SCHMIDT-HAMBURGER et al. (2023). The selected areas show different streetscapes which made them suitable for the following analysis.

(1) Berliner Platz is located at the eastern end of the inner-city ring road 'Am Wall'. It is characterised by an extremely high vehicle load (evening peak with 3.633 vehicles/h and 345 bicycles/h). The bike lanes mostly show widths below standard, partly <1.5 m. In addition, bus lanes and high pedestrian volumes exacerbate the use of space (HEINKE, 2022).

(2) Katharinenstraße is one of Osnabrück's 'Bicycle Streets' with mixed traffic. It originates in the west outside the inner-city ring and ends at the inner-city ring.

Figure 5. Density map ("heatmap") of the MOS in Osnabrück (1:20,000) with focus areas Berliner Platz (1), Lotter Straße (2) and Katharinenstraße (3). Radius 30m with a maximum count of 25. (own figure based on OSM contributors. 21.06.2023).

To reach the city center waiting at traffic lights is necessary. Katharinenstraße is highly frequented, but narrow for cycling volumes (pulks), overtaking is not possible. Left turners have no striping/space around to avoid possible oncoming traffic (HEINKE, 2022).

(3) Lotterstraße/Am Wall: This intersection is northwest of the city center. Very high traffic volume and the lack of objective safety already resulted in a temporary reconstruction (From the north). The bike lane was moved to the edge of the roadway and is now protected. Currently still under construction, which narrows the space. From the other directions the cyclists either ride on the bike lane in the middle of the road (from the west) or on the bus lane (from the south) (HEINKE, 2022).

Berliner Platz (Figure 5 (1) and figure 6) shows the highest accumulations of MOS in the research area were identified. This main intersection is characterized by high amounts of motorized traffic connecting the ring around the city center with one main artery leading out of the city to the east, the Wittekindstraße. Including the main bus routes the intersection also handles high amounts of bike traffic, as the data shows. Besides dedicated bus lanes, the distribution of street space is mostly dominated by 4–6 lanes, including turning lanes, for motorized individual traffic. The bike infrastructure here is characterized by painted bike lanes. There is no separation in construction by bollards, curbs, or other measures. At the same time turning lanes for car traffic are crossing the bike lanes and cyclist turning left are expected to wait in the middle of the intersection waiting for their signal.

In further investigation, the situation and potential stressors at those spots must be observed with camera systems. Surely factors such as time of day and quantity of vehicles must be considered to obtain are more differentiated picture, especially on the effect of streetscapes, especially the design of bicycle infrastructure. Therefore, a comparison of morning or evening peaks at different cycling infrastructures would be favourable. The analysis of the three study areas showed the following results, underlying some early findings of the research conducted concentrating on two major intersections and Katharinenstraße a main bicycle route converted to a 'Fahrradstraße' in 2011 (MARTNS, 2011).

Figure 6. The main intersection of Berliner Platz. (Maximilian Heinke).

In summary, Berliner Platz can be named as a standard example for the design of many major intersections in German cities, including design choices standardized by main guidelines like the RAST, which are discussed in the section above (FGSV, 2006). The amount of MOS in this area shows the need to rethink design choices in the light of subjective safety and the general quality of bike traffic especially in intersections. Further analysis aims to prove the hypothesis mentioned above, questioning intersection designs mainly focused on red paint with no real protective measures, besides aspects like traffic speed and street width.

In addition, Lotter Straße (Figure 5 (2) and Figure 7, left) is another main intersection in Osnabrück that shows similar characteristics as Berliner Platz in its spatial relationships within the city, the inner-city ring, and outgoing main streets. The intersection Lotter Strasse, Natruper-Tor-Wall was redesigned converting one turning lane into a designated and protected lane for bike traffic. Additionally, the number of turning lanes and the general design of the intersection is very comparable with the situation at Berliner Platz. The research does not provide data before the redesign, but the MOS analysis shows some evidence of improving stress levels in comparison to Berliner Platz, which can be related to the redesign of the northern leg of the intersection. To confirm those findings further analysis is needed evaluating the questionnaires and other data comparing the findings at both intersections.

In summary, the data shows high amounts of stress levels or rather high accumulations of MOS. Relating problems in the design of those major intersections like this are discussed in literature and mobility panels under the aspect of subjective safety. Here protected intersections and roundabouts standardized in Dutch traffic guidelines (RIK DE GROOT, 2016) can be named as a possible design solution, that needs to be further examined using the methodology detailed in Chapter 5, adding quantifiable data to the discussion of road distribution objective and subjective safety of different street users, especially considering the needs of pedestrians.

Katharinenstraße (Figure 5 (3) and Figure 7, right) shows rather interesting findings. The street was redesigned as a bicycle street still allowing motorized traffic but giving cyclist priority. The data shows high amounts of trips using Katharinenstrße on different routes leading from east to west. At the same time, MOS data shows rather high amounts of stress. A closer examination of the street shows a high number of cars parking at a 45-

Figure 7. Protected bike lane of Lotter Strasse – Natruper-Tor-Wall (left) and the bicycle street katharinenstraße (right). (Maximilian Heinke).

degree angle with the street switching sides from north to south in between parking cars. In general, the street isn't characterized by high amounts of motorized traffic, so other possible stressors need to be further examined through questionnaires and further data analysis. At the same time the legal set-up of the 'Bicycle Street' can be questioned concerning qualitative bike infrastructure not accompanied by real design changes including the reduction of street-side parking.

5. Outlook and discussion

Concerning the topic of Citizen Science and the experiences from the project presented here, it must be stated that the acquisition of participants is strongly dependent on the support from the respective city. Or, to put it the other way around: without the direct involvement of the municipality, including the corresponding personnel, a long-term study supported by volunteers cannot be carried out. In the two model cities of Ludwigsburg and Osnabrück, very different experiences were made in this regard within the framework of the ESSEM project. Thanks to the enormous support of the city administration and the local press, almost 300 test persons were recruited for the initial data collection in Osnabrück. In Ludwigsburg, on the other hand, the proportion of potentially interested participants was only 10% compared to Osnabrück. This was although the German Bicycle Club (ADFC) addressed its members directly. This may be justified by the respective basic conditions of a city, i.e. the cycling-specific DNA, the existing modal split, or also the topography (ZEILE et al., 2023). Apart from this, it is clear from the experience of the citizen-science approach of ESSEM that participation in explorative processes – and thus their success – must be supported by the political legitimation of the respective city. Also, relevant institutions (schools, churches, associations of people with disabilities, etc.) should be included in an acquisition plan at an early stage to ensure the greatest possible diversity in data collection.

Beyond these identified current and future challenges, the research presented will now be discussed in comparison with other studies using psychophysiological data. In particular, the chosen method, the study design and procedure, and the results obtained will be addressed. Through the consistent development of the Level of Traffic Stress criteria according to MEKURIA et al. (2012), consistent criteria for network links and nodes have emerged that, because of their sectional classification, help policymakers and the public to understand cyclist stress more easily and, for the first time, do not require variable intensive data sets. Many 'bikeability indices' use this method. In combination with Geller's four groups of cyclists, the basis is laid for many cycling studies and the present approach, which attempts to develop this further, where not only nodes and sections but also specific areas can be observed. The combination of psychophysiological 'stress data' with indexes from geodata improves both methods: On the one hand, the calculation rules can be checked again, and on the other hand, special suspected areas can be predefined in advance of studies to see whether a higher stress level prevails there.

The assessment of stress-inducing causes during cycling by comparing co-occurring video recordings, interviews, and stress triggers was carried out by GROß and ZEILE (2016) and Merk et al. (2021). In conjunction with the study 'Safety and Usability of Marked Cycling Routes' (RICHTER et al., 2019), it was thus possible to compare the main causes of stress on cycle protection lanes, in mixed traffic as well as on protected cycling facilities. All studies have in common that almost all groups prefer protected cycle lanes and that the biggest 'stressors' for cyclists are overtaking vehicles, unclear routing, left turns on larger roads and encountering pedestrians or like Texeira stated: 'On a shared sidewalk, primary road, on cobble-stones, on off-road (unpaved) surfaces, or in a noisy place' (TEIXEIRA, 2019). How this can be countered in planning and spatial terms must be decided following the situation.

Technologically, as described above, GSR measurements with the E4 band are reliable in both pedestrians and cyclists and also in different weather conditions (OSBORNE, 2019; SHOVAL et al., 2018; BIRENBOIM et al., 2019; WERNER, 2020), an enrichment of heart rate variability results as Paül I Agustí et al. (2019) did it with pedestrians is an interesting approach, but requires a longer calibration time before the respective experiment, and is thus only useful for experiments with predefined routes in a monitored period.

Another difficulty to be addressed in the project at this point is the (still) limited significance of the data analysis. The study design required participants to ride bicycles in everyday life to rule out MOS associated with study participation, so-called 'study effects'. The marked variation in routes and travel times severely limits the comparability of participants' MOS patterns. Furthermore, future investigations should focus on comparing peak hour street patterns to provide more detailed information and opportunities to restructure intersections, e.g. to make traffic signal timing more bicycle-friendly. In this case, the analysis of the routes traveled shows that some streets or even areas were avoided altogether because the participants knew in advance that it was not convenient to ride a bicycle there (SCHMIDT-HAMBURGER et al., 2023). A significant example is the main multi-lane road 'Am Wall' in Osnabrück. This assumption was substantiated by responses from participants at a workshop in July 2023. Predefined routes, such as those used in the approach of WERNER et al. (2019), can help in this context. They form a reliable basis if certain 'stress hotspots' have already been identified in the course of the preliminary investigations. Checking these points in guided tours is also a new task in the ESSEM project.

Additionally, patterns of MOS by various personal dispositions such as gender, age, or bicyclist type could not be considered for the time being. Besides the small number of participants, the ratio of MOS to the number of trips made by bicyclists must also be included in the analysis for a meaningful statistical analysis. It is worth pointing out that this study and the other studies conducted by ESSEM focus mainly on the cycling domain at this point. Moving forward, it will be important in future studies to consider the entire transportation system when looking at emotional responses.

Following on from these findings, it is planned to eliminate these restrictions as far as possible in the project phases coming from September 2023. First, more test rides will be conducted, increasing the number of participants from 26 to about 120. In addition, a study design with pedestrians is being considered. To account for the non-comparability of the results provided and to allow studies to examine the role of personal dispositions, an additional study will be designed for spring 2024 to provide reference values. This study will be conducted during rush hour, will follow a pre-designed route that includes bypassed streets such as the inner ring road, and will be representative of all participants who participated in the prior studies. Complementary to the spatial analysis, the data analysis is carried out using statistical group comparisons and cluster analysis

(SCHMIDT-HAMBURGER, 2022). It is the aim here to conduct an in-depth analysis focusing on the quality of the perception of negative emotions as inhibiting factors for cycling in Osnabrück.

6. Conclusion

Now that an overview of the previous data collection phases, methods, and initial findings of the project have been provided, the most important points will be summarized. The main goal of this study was to gain information about inhibiting factors in cycling. As part of the BMDV-funded project 'ESSEM', 26 cyclists were equipped with sensor wristbands that measured their stress level whilst cycling in Osnabrück. In total, almost 12,000 so-called Moments of Stress (MOS) could be identified, geolocalised, and visualized. Further analysis highlighted three 'stress hotspots' where the cycling infrastructure differs. In doing so no mentionable results concerning the streetscape could be pointed out. This means that MOS occurred on protected bike lanes, in mixed traffic, and so on. Most hotspots are located at intersections where different modes meet, and the situation is unclear.

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