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Healing the city: a diagnostic approach to decoding stress in urban public spaces

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ABSTRACT
Massive structural interventions and rising density pressures have made urban public spaces increasingly perceived as stressful. From a human perspective, they frequently lack attractiveness. In response to this loss of significance, the method presented here introduces a diagnostic approach to identifying the causes of stress in urban public spaces, which have long remained a Black box in urban research. It provides planners with a tool to assess how dense urban areas are perceived and experienced by people. The diagnostic part of the approach involves identifying the causes of individual stress reactions through a systematic analysis of various measurable and observable characteristics of urban public space. As a key innovation, it integrates *quantifiable hard factors* with *qualifiable soft factors* within a unified analytical framework. The method organises the findings in a *Stressor Matrix*, facilitating a systematic evaluation of urban environments. The method's core principles and components are presented based on a case study in the German city of Würzburg, one of five analysed case studies of this paper. Finally, it presents initial insights into six neuralgic stress-inducing factors, which are *shopfront zones, public space elements, street space organisation, traffic, parking* and *acoustics.*

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Introduction

Relevance and problem statement

Public spaces have historically shaped cities' physical and social fabric, serving as fundamental structures for public life and reflecting the essence of the traditional European city (Kostof and Castillo 1992, Deutscher Städtetag 2006, Cozzolino and Moroni 2022). However, in recent decades, their role has undergone a profound transformation. Extensive structural interventions driven by car-oriented urban redevelopment and increasing densification pressures have significantly altered the character of urban public spaces, particularly in high-density areas (Gehl 2011). As a result, these spaces can be more frequently experienced as stressful environments and often lack the qualities that contribute to attractiveness and a human-centred quality of life (Moore 1997, Krefis *et al.* 2018). Ultimately, this shift has led to the degradation of urban public spaces into mere traffic corridors, stripping them of their role as livable zones of well-being.

If we aim at transformation towards more human-centred urban public spaces, it is essential to examine the issue from the human perspective first. The following symptoms accompany the loss of significance of public spaces in our cities: people increasingly perceive urban public spaces negatively, experience more negative emotions in these spaces, and witness an escalation of stress-related phenomena (Evans 2003, Guite *et al.* 2006, Lederbogen *et al.* 2011, Gado *et al.* 2024, Mehran *et al.* 2024). These are unmistakable signs of an unhealthy city, highlighting the urgent need to identify these stressful spaces and examine the underlying factors contributing to their distress. In this context, it is evident that many factors influence human perception of urban public spaces. These include factors with negative effects such as noise pollution, air pollution, and overcrowding (Guite *et al.* 2006, Zhang *et al.* 2023, Zijlema *et al.* 2024). At the same time, there are also those that have a positive effect, such as visibility, pedestrian activity and vegetation (Hillier and Hanson 1984, Kaplan and Kaplan 1989, Gehl 2011).

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To address the complex transformation challenges in dense urban areas, holistic approaches to cause analysis are indispensable. Current approaches demonstrate that it is insufficient to consider the issue solely from a traffic planning or urban planning perspective. Therefore, planning praxis requires tools that allow to analyse unhealthy urban public spaces from a human-centred scale in a more comprehensive way.

This paper introduces a method that decodes human perceptions in dense urban public spaces. It provides planners with a tool to evaluate dense urban areas' suitability for pedestrian and bicycle traffic. The method employs a holistic approach to analysing environmental factors and assessing their influence on human perception and the development of stress.

State of research

Urban perception & stress detection

The perception of one's environment is deeply rooted in the human being's original, natural way of life. As people move through spaces, they continuously process the environmental stimuli affecting them unconsciously (Mehrabian 1987). According to Selye's underlying stress theory (*Response-Based Model of Stress*), people react to the same stimuli (*stressors*) with the same physical response or stress reaction (Selye 1956). During this stress response, the body releases stress hormones that activate the *Autonomic Nervous System (ANS)* in *arousal* to restore the balance of physiological body functions, called *homeostasis* (Cannon 1914). Arousal represents the level of autonomic activation triggered by an event, ranging from calm (low) to excited (high). Measurable changes include alterations in heart activity, sweat gland activity, and skin temperature, which serve as clear indicators for detecting a stress response (Boucsein 1988, Chrousos *et al.* 1988).

In contrast to arousal, valence refers to the level of comfort an event induces, ranging from negative to positive (Bestelmeyer *et al.* 2017). Ultimately, these activations lead to either a positive response (approach) or a negative response (avoidance). This negative response, or negative activation, is commonly called a stress reaction. Therefore, the *phenomenon of stress* encompasses the totality of an individual's physical and psychological responses to various environmental influences (Werdecker and Esch 2019).

In this regard, the urban context presents an environment with an exceptionally high volume of stimuli. In a natural everyday situation, a person moving through the city encounters a variety of positive and negative stimuli, which, due to their sheer volume, can no longer be clearly distinguished from one another (Mehrabian 1987). This high volume of stimuli produces a highly selective perception of urban public spaces comprising individual fragments and partial images (Lynch 1960). Depending on which partial image predominates or which stimuli are more dominant, this leads to positive emotions, such as safety and well-being, or negative emotions, such as stress.

As previously explained, the detection of negative emotions, or stress, is based on measurable physiological reactions in the human body when confronted with a stressor. In this context, the methodology of *Emotion Sensing* provides research and planning practice with a reliable method for detecting negative emotions in (urban) environments. When confronted with a stressor, this detection of negative emotions, or stress, is based on measurable physiological reactions in the human body. Measuring, locating, and visualizing stress in the urban context are the cornerstones of the methodology known as *Emotion Sensing*, or *EmoCycling* in the context of cycling (Zeile *et al.* 2021; Haug *et al.* 2023a). Unlike other approaches, which rely on targeted questionnaires and thus self-assessments by the participants (Knöll *et al.* 2014, Bieliek *et al.* 2015), this method of stress detection deliberately focuses on the subconscious physiological reactions in the human body. This has a significant advantage: the measurement results are, in a broader sense, impossible to falsify, as it is doubtful that anyone can influence their physiological reactions.

The origins of *Emotion Sensing* can be traced back to Christian Nold, who developed his *bio-mapping* device in 2009 to create *Emotional Cartographies* (Nold 2009). This innovation enabled, for the first time, the geo-referenced recording and visualisation of measurable stress or arousal states within a situational and spatial context. Over the subsequent period, further research works focused on developing various approaches to the monitoring of stress in real-world urban environments, which led to the generation of the first urban stress mappings (Zeile *et al.* 2010, Resch *et al.* 2015, Osborne and Jones 2017, Birenboim *et al.* 2019). There is a wide range of physiological indicators (including e.g. galvanic skin response, heart rate variability) using wearable sensors such as wristbands, *Electrocardiogram (ECG)* chest strap or mobile Electroencephalogram (EEG) (Aspinall *et al.* 2015, Roe and Mondschein 2023, Tawil and Kühn 2024). Each of these settings has its own specific advantages and disadvantages. *Electrodermal Activity (EDA)* sensors, used for *galvanic skin response (GSR)* measurements, are typically worn on the wrist, making them less intrusive and more comfortable for long-term, daily use compared to *EEG* (which requires scalp electrodes) or *ECG* (which often requires chest electrodes). In addition, *GSR* is the most commonly used biosignal in wearable stress detection studies, particularly in field settings (Klimek *et al.* 2025). For integration in everyday life situations, *EDA* sensors are cheaper and easier to implement than *EEG* or *ECG* systems, especially in mobile or urban settings, and signal processing is relatively simple (Singh *et al.* 2025). As part of developing the *Emotion Sensing* measurements used here, several predecessor projects tested different physiological indicators and sensors for their suitability in measuring stress during cycling and walking in an urban, real-world environment (Kyriakou and Resch 2019). The *Emotion Sensing* setting used in this research work involves two measurable indicators detected by *EDA* sensors: skin conductivity *(GSR)* and skin temperature (*ST*). A significant advantage of this measurement method is that the sensor is worn like a smartwatch, allowing test subjects to remain relatively unrestricted while wearing it. In the context of cycling, in particular, this is often difficult to achieve in other settings because measuring devices worn on the finger or around the chest can significantly distort the riding experience and, consequently, the perception of stress. Furthermore, the indicators of skin conductivity and skin temperature are well-suited to detect short-term changes with high accuracy. This has the advantage that no prior calibration of the test subjects or query of health data is necessary to evaluate the measurement results. For this reason, it is highly suitable for cycling, as it allows for the measurement of participants' emotional states second-by-second (Höffken *et al.* 2014).

During the process of *Emotion Sensing* measurements, the two indicators (*GSR* and *ST*) are linked to a smartphone (see Figure 1). They are matched with the corresponding *GNSS signal (Global Navigation Satellite Systems, GNSS)* for location tracking (Zeile *et al.* 2014). Stress is identified during the algorithmic evaluation of the measurement data when skin conductivity increases temporarily while skin temperature drops (Kyriakou and Resch 2019). The analysed results are then presented as heatmaps, visually displaying where participants experienced stress while cycling or walking within the urban environment (see Figure 1).

Cause analysis in urban environments

Building upon the current state of stress research, various studies focus on the causes of negative emotions in the urban context. Not all of these studies, however, explicitly address the phenomenon of stress. Many studies explore the topic within a broader context, such as examining comfort during cycling (Li *et al.* 2012, Gao *et al.* 2018) or specific behaviours in urban public spaces (Gehl 2011, Trop *et al.* 2023). Nevertheless, these research areas provide valuable insights for the presented methodological approach.

The presented research projects originate from transportation research and urban planning. Transportation research approaches primarily focus on *quantifiable hard factors*, whereas approaches from urban studies predominantly deal with

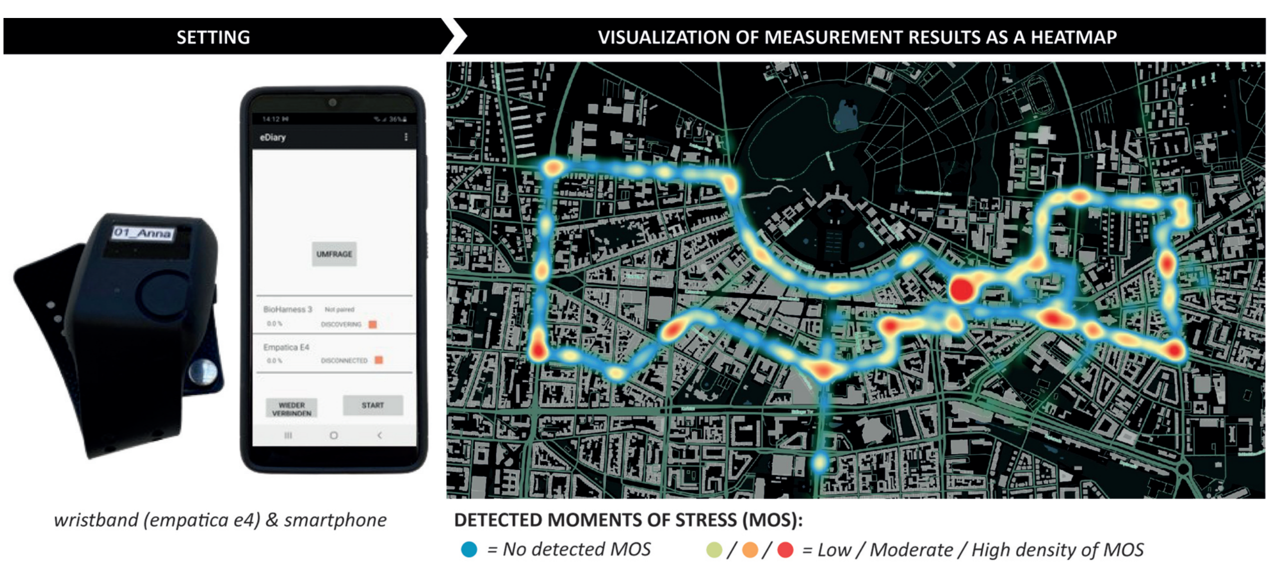

Figure 1. The setting of Emotion Sensing measurements and visualisation as a heatmap in Karlsruhe, Germany. Source: own representation using the data source cape Reviso (HLRS, 2020).

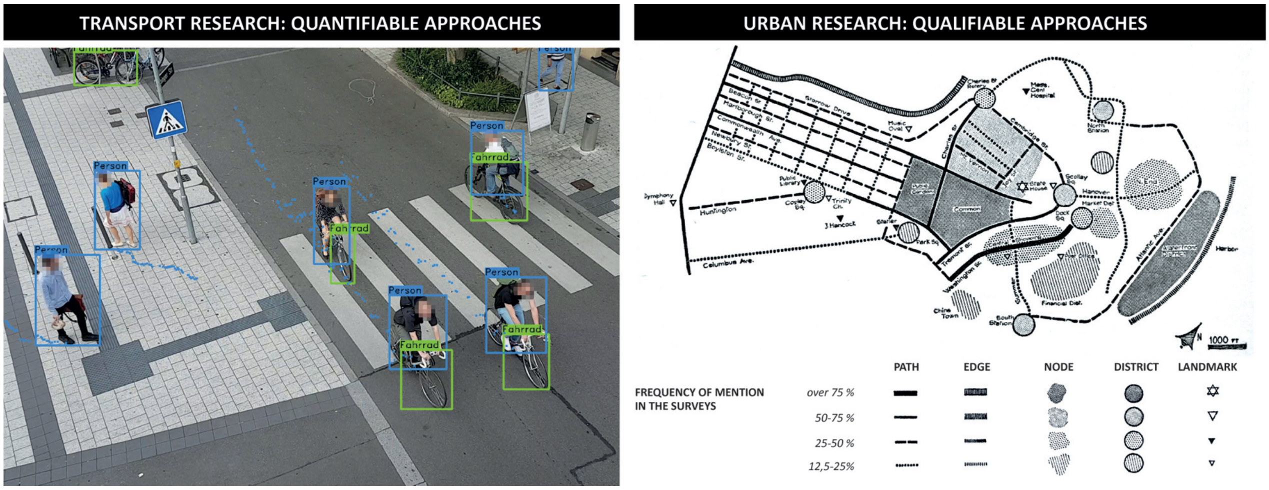

Figure 2. Different cause analysis approaches in transportation research (left) and urban research (right). Source: left side: cape Reviso project (HLRS, 2020); right side: mental map of Boston (Lynch 1960).

qualifiable soft factors. Figure 2 vividly illustrates the crucial differences in these two research fields' thematic and methodological focus.

Hard factors & quantifiable analytical approaches. The discipline of transport research – particularly in cycling research – is considered a pioneer in stressor analysis. The primary focus is analysing and quantifying traffic-specific and infrastructure-specific factors using sensor-based measurement techniques.

A well-established method for collecting traffic data is quantitatively counting different road users and traffic densities. In this context, recent approaches have increasingly applied these methods in motor vehicle traffic, cycling, and pedestrian mobility (Pratt *et al.* 2014, Roll 2021). By quantitatively recording traffic dynamics, researchers analyse traffic volumes across different times of the day, days of the week, and seasons. In addition to traditional counting stations, high-resolution camera systems combined with *machine learning* for image analysis are increasingly used to assess traffic volumes, densities and movement patterns of various road users (Zeile *et al.* 2024). These intelligent systems enable real-time object detection, allowing for the automated and simultaneous identification and categorization of different road users over extended periods.

Furthermore, cycling research has benefitted from the widespread use of smartphones and the growing popularity of social (sport) networks. In this context, the smartphone serves as a ubiquitous and multifunctional sensor, offering diverse possibilities for collecting movement and environmental data related to cycling (Temmen 2022). Various, mostly freely available applications provide a low-threshold means of data collection and integrate easily into the everyday routines of participants. A research project funded under the National Cycling Plan, *Big Data in Cycling*, conducted by the Technical University of Dresden (Lißner and Francke 2017), explored the applicability of cycling data from providers such as *Strava* and *BikeCitizens* for municipal cycling evaluation and planning. The provided data, processed using Strava's analysis functions, enabled the correlation of parameters such as cycling speed and waiting times (e.g. at traffic lights) with frequently used or avoided route segments.

In other research projects, smartphones collect data from sensors that can be flexibly attached to bicycles. These studies aim to assess the quality of urban cycling infrastructure based on sensor data recorded during participants' everyday journeys. The collected data enable detailed analyses of surface conditions, delays and waiting times at junctions and signalised intersections (Schering *et al.* 2022, 2024).

Soft factors & qualifiable analytical approaches. The previous examination of transportation research has already highlighted traffic-related stressors as a key area of causal research. However, analysing urban public spaces is equally essential for a comprehensive understanding of stress in dense urban environments – yet remains underexplored. The following section examines historical and contemporary approaches in urban research and perception studies, expanding the focus to include practical insights from architecture, urban planning, and artistic methods. Alongside digital and quantifiable techniques, different research approaches explore the potential of analogue and qualitative urban research methods for stressor analysis.

The work of architects and urban theorists Kevin Lynch and Robert Venturi is particularly influential. As early as the 1960s and 1970s, they developed analytical methods for studying urban public spaces, frequently employing mapping as a key tool (Lynch 1960, Venturi *et al.* 1979). Unlike conventional geographic maps, mapping in urban research is not merely descriptive but serves as an analytical method to identify urban characteristics (Pelger *et al.* 2021). It is inherently interpretative and shaped by the subjective engagement of its creator (Seggern Hille *et al.* 2008). Venturi's use of mapping in Learning from Las Vegas (Venturi *et al.* 1979) illustrates its role in visualizing qualitative urban factors. His analyses emphasise the narrative and symbolic nature of mappings and their potential for abstraction. His work focuses on architectural semiotics, the boundaries between public and private spaces, and the spatial character of the Strip as a commercial hub. Using a consistent scale and graphical style, he effectively compares urban elements.

Mental mapping is another key cartographic method in urban research (Lynch 1960). This technique captures subjective memories, perceptions, and experiences of urban public spaces, offering insights into the perceptual relevance of various urban elements (Million 2021). In interviews, participants draw a city space from memory, which is then analysed to identify recurring structures perceived as defining the urban landscape. In 'The Image of the City' (Lynch 1960), Lynch studied the American cities of Boston, Jersey City, and Los Angeles, identifying five key elements: paths, edges, nodes, districts and landmarks. These were symbolised as points, lines, and areas in mental maps, with their depiction varying by frequency of mention. This method visualises locations that shape urban perception and highlights the subjective significance of different city elements.

Beyond cartographic methods, visual analysis is another important tool in urban research (Eckardt 2014). This tool involves qualitative documentation of spatial observations, primarily through photography and sketches. While not widely used in other disciplines, it is essential in urban studies. Jan Gehl's research is particularly influential in this field (Gehl 2011, p. 45). In his work, Gehl focuses particularly on urban public spaces and the activities occurring within them. He analyses human behaviour in urban public spaces, mainly using photography to convey his findings visually.

Research gap, objectives & research questions

The preceding section shows that negative emotions in urban contexts can be reliably and objectively detected in a quantitative way using *Emotion Sensing* measurements based on physiological stress responses. However, investigating the manifold causes of these negative perceptions of urban environments remains highly fragmented across different research disciplines. The few approaches in the research field focusing on analysing stressors in cycling and walking primarily examine specific, *quantifiable factors* such as waiting times at junctions (Schering *et al.* 2022) or traffic densities (Zeile *et al.* 2024).

Therefore, more holistic approaches are needed to integrate various qualitative and quantitative research methods into a unified analytical framework. The proposed approach addresses this research gap, introducing a more holistic stressor analysis method. As a key innovation, the method integrates the analysis of *quantifiable hard factors* with *qualifiable soft factors* within a unified analytical framework. This integrative approach lays the foundation for a more comprehensive, human-scaled understanding of urban public spaces. It enables urban research to support the transformation of our cities in ways that promote urban well-being and a high quality of life.

The proposed methodological approach aims to develop a tool to analyse and evaluate the qualities of urban public spaces in the early stages of planning.

With this objective, the proposed methodological approach addresses the following research questions:

(1) What do negative emotions mean in the urban context, and how can they be measured?
(2) Which hard and soft investigative factors can represent the complex urban environment?
(3) How can the spatial analysis of both quantifiable and qualifiable factors be equitably translated into a comparable format?
(4) Which factors are associated with the emergence of stress?

Concept

This research bases its concept on the assumption that negative emotions and stress in urban environments can be detected and spatially located through sensor-based measurements (*Emotion Sensing*). Consequently, the maps from selected *Emotion Sensing* studies conducted in various cities serve as a foundation for this research. Specific stress hotspots identified in these maps will be chosen as case study areas to investigate potential causes further.

The aim is to examine a diverse range of urban public spaces across different cities, all exhibiting elevated stress levels. This research analyses a broad spectrum of quantifiable and qualifiable factors within these case studies. Accordingly, the analytical methods employed will also reflect this methodological diversity. In order to ensure the appropriateness and reliability of the chosen indicators and data collection techniques, the research concept conducts experimental pilot studies in advance. The insights gained from these trials help define a data collection protocol to ensure comparability across the case studies.

The presentation of the case study findings will follow a new methodological approach intended to enable the comparison of highly diverse analyses with regard to both content and method. This approach aims to integrate quantitative and qualitative aspects and data-driven and subjective dimensions into a unified analytical framework. In doing so, the research seeks to examine the causes of stress in dense urban areas as holistically and integratively as possible.

Methodological approach

In order to build upon this conceptual framework, this chapter first introduces the data collection process. Subsequently, the two newly developed methodological components – which form the core of the approach presented here – are outlined. The section concludes with a detailed outline of the evaluation procedure.

Data collection

This first section introduces the defined investigative factors, underlying analytical methods, and data sources. The applicability of this data collection plan was evaluated and adapted through experimental test runs within the framework of the *Decoding Stress* study at the *Karlsruhe Institute of Technology*, within a study area in downtown Karlsruhe. The work of Haug *et al.* (2023b) presents the detailed study results. Therefore, the following section will only present the most important findings as preparation for the case studies.

Investigative factors, analytical approaches & data sources

The composition of the thematic areas and investigation factors results from the aforementioned test runs. In the initial stage, numerous site visits and observations led to the identification of six thematic areas and thirty-eight investigation factors. Subsequent test runs then reduced these to a manageable set of five thematic areas and twelve investigation factors (for further details see Haug *et al.* 2023b, 2024). This range aims to represent the spatial situation of the studied urban areas and the human sensory perception as entirely as possible. The five thematic areas, therefore, not only bring together factors related to the built environment, open spaces, design, and traffic aspects of urban public spaces but also deliberately include their olfactory and acoustic aspects. Table 1 lists the topics, the investigative factors and their specific parameters.

Due to the broad spectrum of defined investigative factors, the associated analytical approaches and data sources also exhibit high variance. However, by categorising the investigative factors and parameters into *quantifiable* and *qualifiable* approaches, the specific analytical methods and data foundations could be further refined during initial experimental investigations in the *Decoding Stress* study. The study demonstrated that the following three methodological approaches, or a combination, represent the environmental factors occurring in dense urban public spaces more comprehensively. Table 1 presents the methods employed across the various investigative factors.

Two-dimensional data sources. Some of the investigative factors are analysed using two-dimensional digital datasets. The primary data sources include freely available *OpenStreetMap* datasets, aerial imagery, and geospatial data provided by municipal geoportals. This method is particularly suitable for investigating parameters whose characteristics can be assessed solely from a bird's-eye view. This study successfully applies two-dimensional digital analysis approaches to the most investigated factors. The only exceptions are the factors related to sensory aspects and those that involve the third dimension.

Three-dimensional remote analysis. For those parameters where capturing the third dimension, or the pedestrian perspective, is essential, three-dimensional remote approaches represent a meaningful analytical method. In this context, insights into the characteristics of each investigative factor are gained, especially by analysing image materials from street-level views, such as the 360° views from the *Apple Maps* provider or video recordings. Like the two-dimensional data analyses, this approach, except for sensory factors, was applied to nearly all the parameters under investigation.

On-site walkthroughs. On-site walkthroughs are an indispensable analytical tool for investigating parameters that include a subjective component and for

Table 1. Overview of the thematic areas, investigative factors, parameters, analytical approaches and data sources. The methods applied are categorised into a (two-dimensional data sources), B (three-dimensional remote analysis) and C (on-site walkthroughs).

			Analytical approach		Methods applied		
Thematic area	Investigative factors	Specific parameters	Quantifiable	Qualifiable	A	B	C
Buildings	1. Building density	1a. Floors	x			x	x
		1b. Parcelling		x	x		
	2. Ground floor zones	2a. Ground floor usage	x		x		
		2b. Forecourts	x	x		x	x
	3. Shopfront zones	3a. Shop windows	x			x	x
		3b. Symbol density	x	x		x	x
Open space	4. Public open space	4a. Open space usage	x		x	x	
		4b. Frequency of use	x	x			x
	5. Public space elements	5a. Trees	x		x	x	
		5b. Fixed urban furniture	x	x	x	x	
Design	6. Pavement	6a. Condition		x			x
		6b. Materiality	x		x	x	
	7. Street space organisation	7a. Zoning	x		x	x	
		7b. Dimensioning	x		x		x
Traffic & movement	8. Traffic	8a. Traffic density	x	x			x
		8b. Traffic participants	x		x	x	
	9. Intersections	9a. Movement flows	x		x	x	
		9b. Crossing facilities	x		x	x	
		9c. Accessibility		x			x
	10. Parking	10a. Parking zones	x		x	x	
		10b. Wild parking	x	x		x	x
		10c. Driveways	x		x	x	
Sensory perception	11. Olfactory	11a. Types of smells		x			x
		11b. Associations		x			x
	12. Acoustics	12a. Types of sounds		x			x
		12b. Sound level	x		x		x
		12c. Associations		x			x

capturing all soft environmental factors (Gehl 2011, p. 45). This method places special emphasis on subjective urban perception. As a key element of this analytical approach, the on-site walkthroughs were documented through systematic recordings of qualitative and quantitative findings using annotated maps, photographs, and sketches in the present case study. For most analysed factors, walkthroughs provide an important control layer and complement the first two methods.

Methodological components

Based on these findings, the newly developed method introduces an approach for cause analysis and stressor identification, enabling the comparable analysis of potentially stress-inducing factors in urban contexts. The methodological framework develops two key components to achieve this: the *Stressor Unfolding* and the *Stressor Matrix* (see Figure 3).

Stressor Unfolding

Using the methodological component of *Stressor Unfolding*, the presented approach develops a translation method that enables the transfer of spatial analyses of various investigative factors into a comparable format. This overcomes the conventional separation between quantitative and qualitative analyses, integrating them into a unified representation for the first time.

The creation of such a *Stressor Unfolding* follows these steps: In the first stage, the data collection plan specifies the investigative factors, along with their corresponding data sources (see Figure 3, left column). At this stage, each investigative factor is further disaggregated into two or three parameters, as indicated in Table 1. Figure 3 exemplifies this process with the equation $F_1 = P_{Ia} + P_{Ib}$, demonstrating the operationalisation of the investigative factor *building density* (F_1) is operationalised through the parameters *floors* (P_{Ia}) and *parcelling* (P_{Ib}). For each parameter, the plan establishes a corresponding data-collection strategy.

In the second stage, conventional spatial analysis plans record the analyses of these factors and parameters (see Figure 3, middle column). These plans mark both the predefined movement path of the investigations and the adjacent or intersecting streets. Using these entries, it becomes possible to transform the spatial characteristics of the study area into an abstract, standardised format similar to a coordinate system. For this transformation, the framework drawn in the spatial analysis plans unfolds into a kind of grid (see Figure 3, middle column). The movement path then forms the x-axis, along which the adjacent streets and intersection points become marked

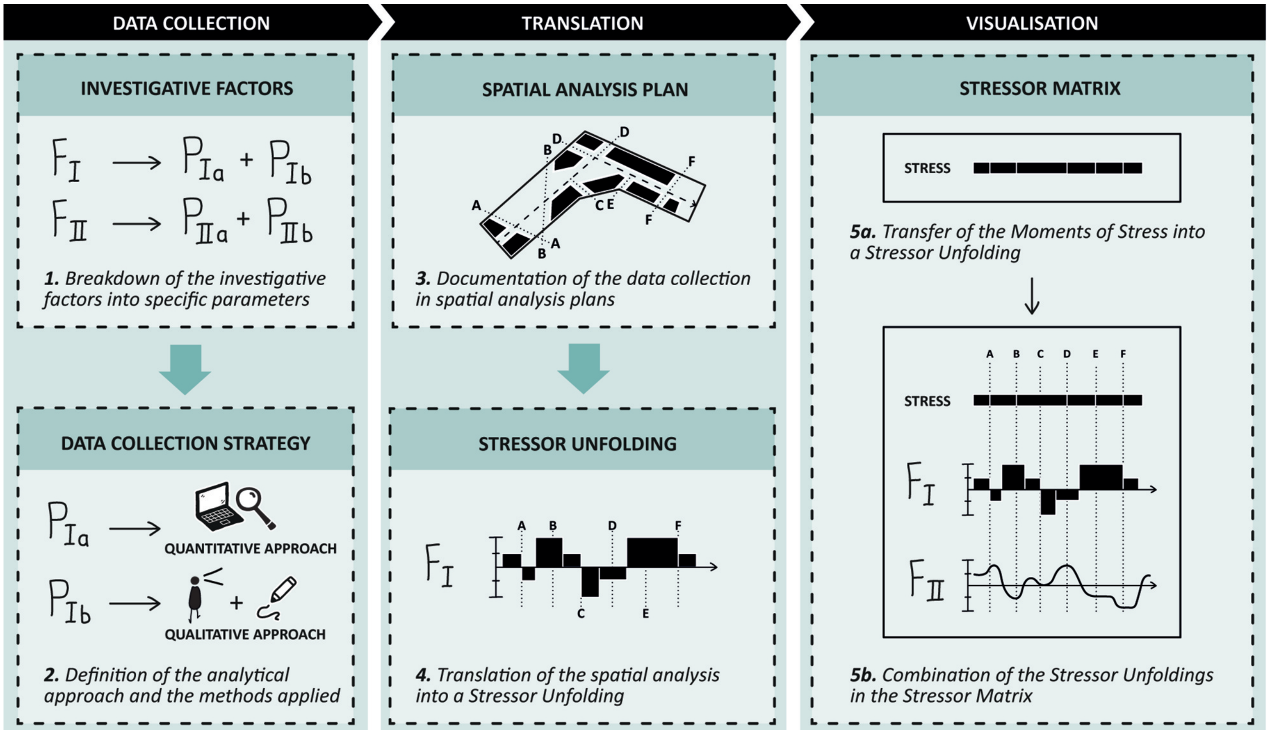

Figure 3. Development of a translation method using the method structure consisting of Stressor Unfolding and Stressor Matrix.

as fixed reference points. The intensity of the analysed factor is then plotted along the y-axis using an individual scale. Within the presented method, this abstract framework is called *Stressor Unfolding*.

This framework then allows for the conversion of absolute values in the real built environment into relative values in the unfolding. The unit and granularity in which the *Stressor Unfolding* transfers the values are regulated by a detailed data collection plan (for further details see Haug 2025, pp. 150–154). The example of the investigative factor, *public space elements*, and one of its parameters, *fixed urban furniture*, clearly illustrates this translation process and its granularity. The data collection plan categorises the *Stressor Unfolding* scale according to different numbers of fixed urban furniture per 10 metres in the real-world investigation area as follows: low furniture density (1 to 3), moderate furniture density (4 to 6), and high furniture density (7 and above).

Stressor Matrix

Once the research created a *Stressor Unfolding* for each investigative factor, these unfoldings are compiled in the *Stressor Matrix* for overall analysis and correlated with the results of the *Emotion Sensing* measurements (see Figure 3, right column). Like a table, each *Stressor Unfolding* occupies a separate row within the matrix. In the top row, the *Stressor Matrix* presents the results of the *Emotion Sensing* measurements as an unfolding. For this purpose, the heatmap – following the same logic as the previously described translation of spatial analysis plans – is transferred into a schematic framework and transformed into a linear representation. A colour coding similar to the heatmaps is applied, using a four-level colour scale to visualise the concentration of measured *Moments of Stress (MOS)*.

Throughout this study, the approach refers to the matrix-like combination of measured *MOS* and the various *Stressor Unfoldings* as the *Stressor Matrix*. It serves as the foundation for the subsequent analysis. Providing a structured and comparative visualisation facilitates identifying relationships between the investigated factors and stress.

Evaluation of the Stressor Matrices

As part of the evaluation, the *Stressor Matrices* and *Stressor Unfoldings* are first analysed individually concerning their stress relationships. In the initial step, the unfolding of the stress measurement is compared sequentially with all *Stressor Unfoldings* of the 12 investigated factors. The individual case study evaluation follows this detailed procedure: First, the evaluation procedure marks all stress hotspots categorised as medium to high stress levels in the stress measurement unfolding. Similarly, the analysis identifies all peaks and troughs, category changes, and other notable patterns in the *Stressor Unfolding* of the investigated factors. This process also compares the position of the marked points along the x-axis. A predefined numerical value is assigned depending on the degree of congruence or incongruence between these points. The assigned individual values range from 0 to 1 and are defined as follows: no relationship to stress (0), partial relationship to stress (0.5) and strong relationship to stress (1.0).

Given the five case studies, each with 12 factors, 60 individual values are assigned in the individual evaluation. Figure 6 visualises the assigned values in the middle column. In the final step of the evaluation, the assigned individual values are summed for each investigated factor to determine the overall relationship to stress (see Figure 6, right column). The sum, derived from the addition of the four individual values from the five case studies per factor, indicates the overall relationship between the investigated factor and the phenomenon of stress.

The resulting overall relationships to stress, ranging from 0 to 5, follow this scale:

- 0 to 1.0: No relationship between the investigated factor and stress
- 1.5 to 2.0: Low relationship between the investigated factor and stress
- 2.5 to 3.5: Moderate relationship between the investigated factor and stress
- 4.0 to 4.5: Strong relationship between the investigated factor and stress
- 5.0: Very strong relationship between the investigated factor and stress

Results

The developed methodological approach and the defined data collection strategy were tested in five case studies conducted in real urban spatial contexts. The case studies took place in three German study cities: Karlsruhe, Osnabrück, and Würzburg. The approach conducted two case studies in Karlsruhe (K1 and K2) and Osnabrück (O1 and O2) and one in Würzburg (W1).

These specific study areas were chosen on the one hand because the *Urban Emotions Initiative* has already conducted previous stress measurements in these cities (Haug *et al.* 2023a; Super Testsite 2024b; Zeile *et al.* 2021). As previously mentioned, the method presented in this paper builds upon the results of these stress measurements as a basis for identifying underlying causes. On the other hand, the cities Karlsruhe, Osnabrück and Würzburg exhibit very different city sizes, modal splits and spatial characteristics, representing diverse use cases for the further testing phase of the developed method.

The first section of this chapter presents the findings of case study W1, selected as a representative example from the five case studies to illustrate the applied approach in greater detail. The detailed presentation of the results from the remaining four case studies is beyond the scope of this paper. The second section then addresses the analysed stress relationships across all five case studies.

Case study W1, Würzburg, Germany

Case study W1 is located in the city centre of Würzburg and is used in the following section to provide insight into the results of the case studies.

Framework

The *Emotion Sensing* data used as the basis for the case study W1 originates from the *Super Testsite* project. The measurements were conducted in the summer of 2024, between 10 and 21 June 2024, with 41 participating pedestrians in Würzburg's city centre at various times of the day (Super Testsite 2024a). The participants moved freely through Würzburg's city centre without a predefined route to capture participants' movement behaviour in a manner that closely reflects real-life conditions, reaching five designated checkpoints. The distribution of checkpoints within the area of the case study and the order in which they were to be passed by the participants ensured that all of them passed the checkpoints in the same direction of movement. This is particularly important when we consider that human perception is highly sequential, meaning that passing through an urban space from A to B may be perceived very differently from passing through it in the opposite direction, from B to A (cf. Bieliek *et al.* 2015).

One of these checkpoints is the area around *Eichhornstraße*, which serves as the focus of the causal research in case study W1. The *Emotion Sensing* measurements revealed significant fluctuations at this location, indicating increased stress levels. Figure 4 shows the heatmap of the measurements on its left-hand side. This map highlights two key areas of heightened stress: a localised peak at the intersection *Semmelstraße/Theaterstraße (1)* and a particularly prominent stress hotspot along the *Eichhornstraße* in the section between Point 3 and 4 where the pedestrian zone transitions into a square-like area. Because of its chequered paving that forms a scannable QR code, the square is nicknamed the *QR Code*.

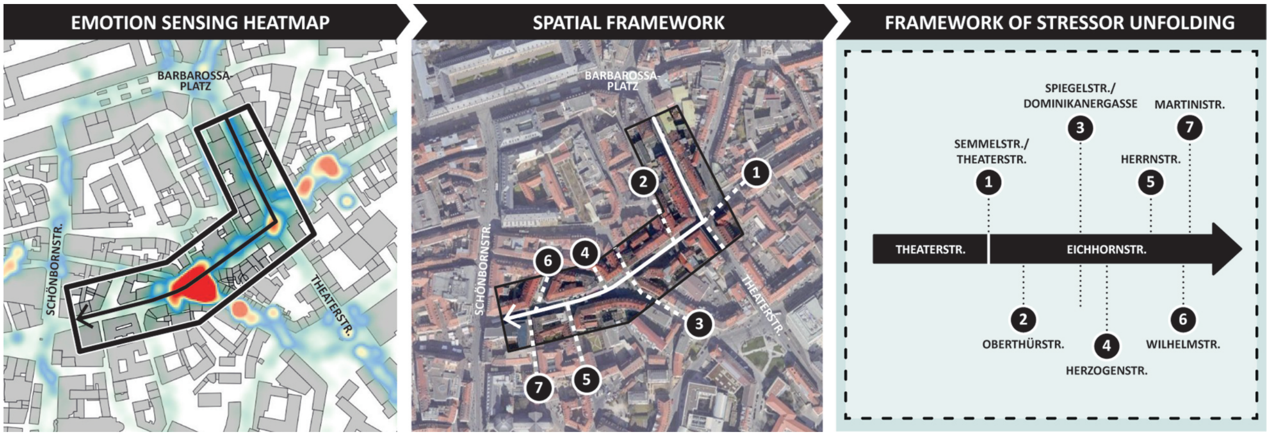

Figure 4. Structure of case study W1, Würzburg: *Emotion Sensing* heatmap, spatial framework and framework of Stressor Unfolding.

The middle and right columns of Figure 4 present the spatial framework and its translation into an abstract structure for stressor analysis to provide a more precise spatial overview of the study area. The framework of the case study defines the approximately 400-metre movement corridor as follows: coming from the railway station towards the old town, the study area begins immediately after *Barbarossaplatz* in *Theaterstraße*, then turns into *Eichhornstraße*, and ends at the intersection with *Schönbornstraße*.

Implementation

The framework, the measurements and the methodological approach have been implemented for the test case to investigate the causes of negative emotions in the urban environment. To this end, this research analyses the 12 study factors and their associated parameters (see Table 1) using the defined analytical methods. In this context, on-site walkthroughs were conducted on Monday, 28 October 2024, in the morning and afternoon, under sunny weather conditions. For the remote analyses, this investigation primarily uses *OpenStreetMap* data, aerial imagery, and three-dimensional image data from *Apple Maps* and *Google Street View*. The analysis results for the 12 factors were each represented in an individual *Stressor Unfolding* and combined with the *Emotion Sensing* data in the *Stressor Matrix*.

Results of case study W1

The following section discusses the key findings of the individual analyses and relates them to the results of the stress measurements. Figure 5 presents an extract of the *Stressor Matrix* W1, showcasing 5 of the 12 analysed factors: *building density, public space elements, pavement, traffic* and *acoustics*. At its top, the *Stressor Matrix* displays the unfolding of the identified *Moments of Stress*.

Moments of stress. As already indicated by the heatmap of the *Emotion Sensing* measurements (see Figure 4, left column), the study area W1 shows two critical stress hotspots. The first hotspot is located at a specific point in *Theaterstraße*, at *Semmelstraße/Theaterstraße* (1), marking the transition to the pedestrian zone. The second stress hotspot, by contrast, is significantly more pronounced and spatially extensive in *Eichhornstraße*, around the *QR Code*, between *Spiegelstraße/Dominikanergasse* (3) and *Herzogenstraße* (4).

Building density. Concerning the investigative factor of *building density*, the research area appears highly homogeneous. In this case, the analysis did not reveal any clear relationship with the recorded stress points. The number of floors is almost exclusively four, and the parcelling of the buildings exhibits a predominantly uniform grain. Except for the street spaces at the immediate intersection points, the built structure of W1 shows two open spaces: the widening of the pedestrian zone around Point 3 and the *QR Code* between Points 3 and 4. No relationships with the results of the stress measurements are apparent.

Public space elements. W1 shows compact and arranged fixed urban furniture throughout the analysed study area. On the left, the fixed urban furniture stands primarily in front of Point 1, within the widening of *Eichhornstraße* between Points 2 and 3, and sporadically around the *QR Code* between Points 3 and 4. On the right, it is concentrated, especially at the junction to *Eichhornstraße* (1), with a high density of bicycle racks, and between *Herzogenstraße* (4) and *Wilhelmstraße* (6).

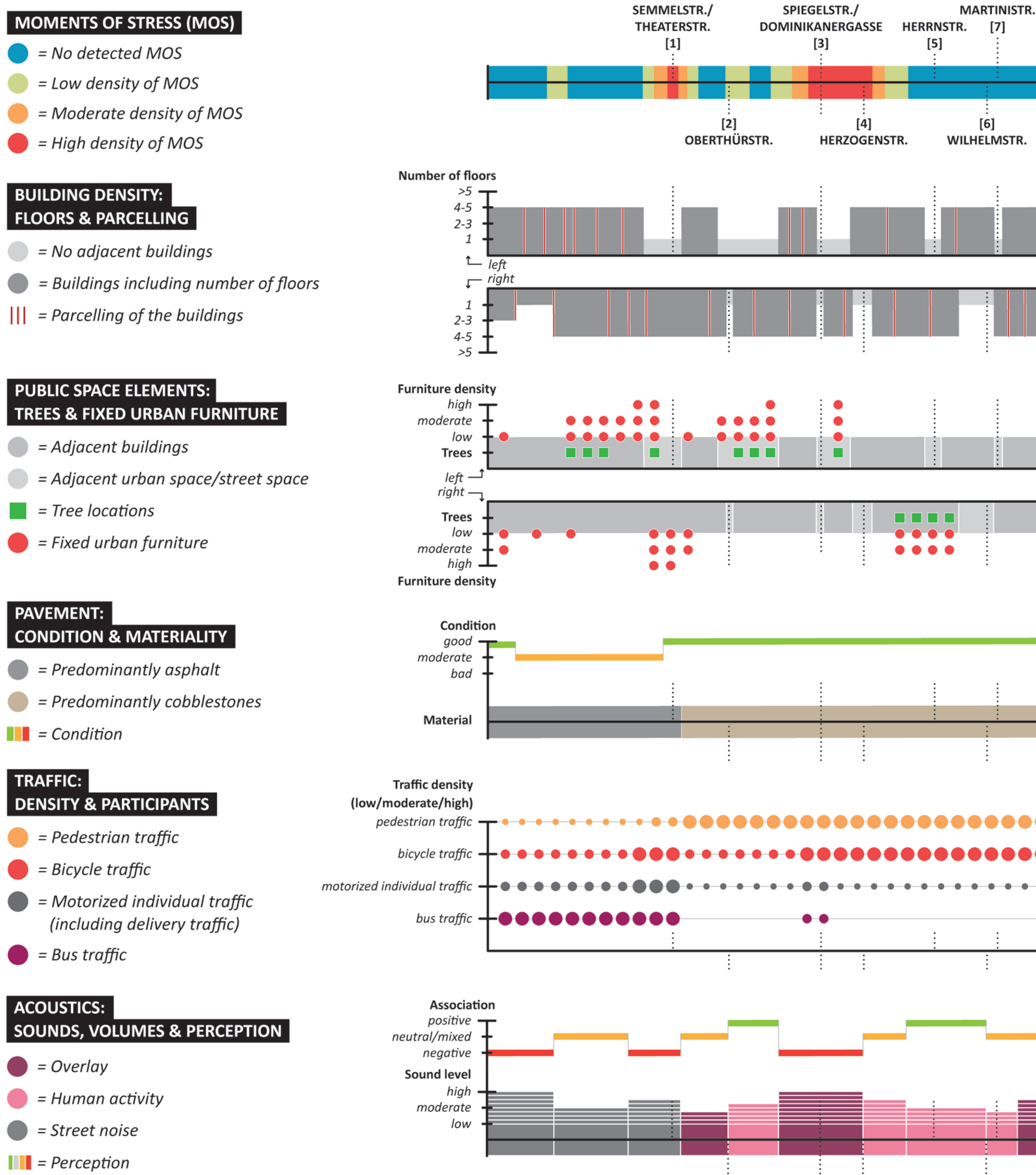

Figure 5. Extract of the Stressor Matrix for case study W1 (Würzburg).

The most significant clusters of urban furniture align with the identified stress hotspots. The trees, except along *Theaterstraße* at Point 1, are integrated into generous urban furniture, located on the left at the two open spaces and on the right between Points 4 and 6.

Pavement. The pavement in the research area consists of two sections: Asphalt predominates in *Theaterstraße* up to Point 1, while the pedestrian zone in *Eichhornstraße* features cobblestones. The condition of the pavement in *Theaterstraße* ranges from medium to good quality. The pavement in the pedestrian zone was newly laid just a few years ago and, therefore, is in excellent condition. Regarding the results of the stress measurements, only the change in surface material at the stress hotspot at Point 1 is

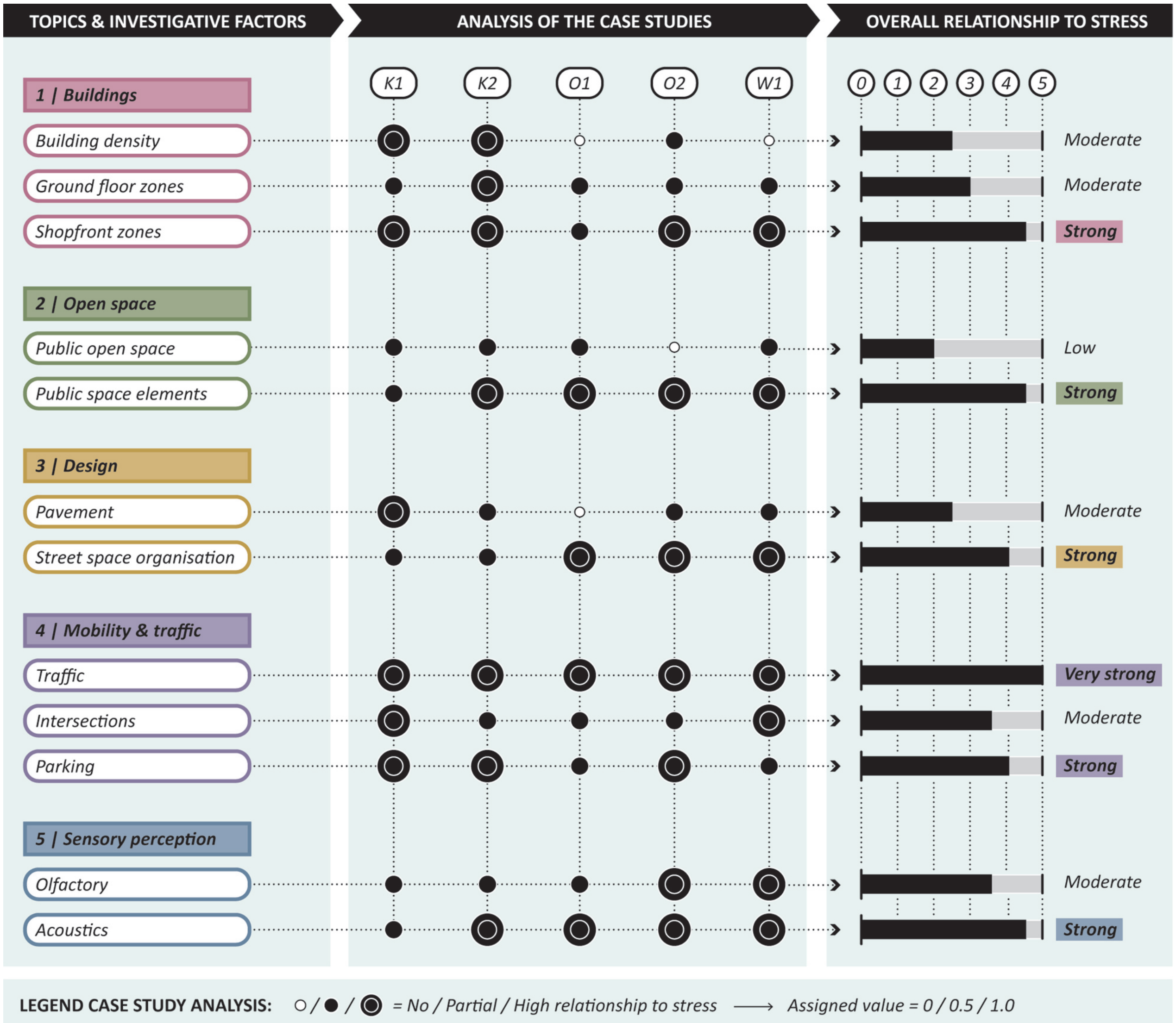

Figure 6. Analysis of the stress relationships of the investigated factors in the case studies K1, K2, O1, O2 and W1.

notable. However, the analysis could not observe any relationships at the second hotspot.

Traffic. The investigative factor *traffic* shows strong relationships with the identified stress hotspots. Along *Theaterstraße* to Point 1, car and bus traffic dominate, with medium density for motorised individual traffic and high density for buses. Bicycle traffic on the main carriageway reaches moderate densities, while pedestrian traffic in side areas remains low. At the traffic light junction at *Eichhornstraße* (1), car and bicycle traffic accumulate, briefly increasing density. From Point 1, *Eichhornstraße* is for pedestrians and cyclists, with significant delivery traffic. Up to the *Spiegelstraße/Dominikanergasse* junction (3), it has high pedestrian density, moderate bicycle density, and light delivery traffic. At Point 3, car and bus traffic intersect, causing brief fluctuations, while more cyclists turn into *Eichhornstraße*, increasing bicycle traffic after Point 3.

Acoustics. The acoustics in W1 show a clear link to the detected MOS. They are dominated by loud street noise in the first section up to Point 1, perceived as negative. After this part, a brief period of lower noise, rated as mixed, follows. At the *Semmelstraße/Theaterstraße* intersection (1), noise increases again, becoming negative. At the entrance to the *Eichhornstraße*, moderate noise persists until the *Oberthürstraße* (2), mainly mixed-rated, meaning that the acoustic perception was rated differently in various situations during the walkthroughs. After Point 2, louder human activity, associated with a positive perception, follows. At the *QR Code*, noise increases and becomes negative. Human activity reappears in the sections up to *Martinistraße* (7), and noise gradually decreases, becoming more positive. In the final part, tram noise along *Schönbornstraße* increases slightly. At this point, the acoustic perception is also rated negatively.

Stress relationships

The following section evaluates all five examined case studies: K1 and K2 in the study city of Karlsruhe, O1 and O2 in Osnabrück, and case study W1 in Würzburg. In the context of this evaluation process, the focus is on identifying the stress relationships among the examined factors. Central to this is the question: What is the relationship between the investigated factors and the stress measurement results?

Figure 6 shows the calculated stress relationships of the investigated factors based on the sample of the five case studies. In line with the research objective of identifying causal relationships, this work focuses on factors with a strong or very strong stress relationship. These factors are, therefore, referred to as influencing factors in the following sections. Specifically, these factors are *shopfront zones, public space elements, street space organisation, traffic, parking* and *acoustics*.

It is particularly noteworthy that, in the evaluation, the investigative factor *traffic* showed a strong stress relationship in all five case studies without exception. As a result, the overall evaluation also shows a very strong stress relationship for this factor. This phenomenon indicates that increased stress levels were observed across the five case study investigations in locations with heavy traffic or with many different road users. Therefore, *traffic* is the most frequent stress trigger in the case studies examined in this work.

Other factors, however, display significant variation across the five case studies. One such factor is *building density*, for which the overall analysis identified a moderate relationship to stress. While the case studies K1 and K2 in Karlsruhe show a strong relationship, the O2 case study reveals only a partial link to stress, and the O1 and W1 case studies show no relationship. The evaluation observes a similar pattern with the factor of *street space organisation*. The overall stress relationship was also rated as strong. However, the distribution across the case studies shows that the stress relationship was only partial in the two Karlsruhe case studies. In comparison, the evaluation detected a strong relationship to stress in the remaining three case studies.

In contrast, the case study evaluation process identified only a weak relationship between stress and the investigative factor of *public open space*. The individual K1, K2, O1, and W1 case study evaluations identified a partial relationship to stress. In the case study O2, no relationship could be detected. This means that stress was measured less frequently in areas with open spaces within the case study investigations.

In general, this shows impressively that there are generalisable factors such as *traffic* that have a demonstrable effect on stress. In addition, there are many other factors that do not always, but under certain circumstances, have a demonstrable effect on stress. An example is *olfactory*.

Discussion

The following section provides an overview of the similarities and differences with empiric results in related research work and addresses some key limitations of the presented methodological framework. Additionally, this section discusses the limitations concerning the broader context of research and urban planning.

This study is the first to examine a vast range of investigative factors and their influence on human stress perception. Several of these factors have not previously been explored within this research field. Other factors, however, have already been examined in other research projects in a similar context and can now be compared with the findings of the present study. The empirical results from the studies by Knöll *et al.* (2014), Knöll *et al.* (2018) and Aspinall *et al.* (2015) represent the most important interfaces for comparing the findings on stress-inducing factors. The results regarding the investigative factors *acoustics* and *traffic* show explicit agreement with the work of Knöll *et al.* (2014) in which study participants evaluated public spaces in terms of their quality of stay. The study also concludes that noise and traffic play a significant role in the experience of stress in public spaces, which underpins the identified *acoustic's* strong relationship to stress and *traffic's* very strong relationship to stress in the presented study here. Knöll *et al.* (2014) and Aspinall *et al.* (2015) and several other research studies also identified the lack of greenery as a common trigger for stress. Here, it is necessary to make a comparison with the present study in a slightly more differentiated manner. The findings obtained here are consistent with the studies listed, as the investigative factor *public open space* also encompasses public green spaces. This factor shows only a low relationship to stress, which supports the findings of Knöll *et al.* (2014) and Aspinall *et al.* (2015). However, the study presented here does not yet take a sufficiently differentiated view of vegetation in public spaces. In the present study, the parameter *trees* is merely summarised under the investigative factor *public space elements* together with *fixed urban furniture* and shows a strong relationship to stress. Here, it would be important to consider tree locations separately or to summarise them with other vegetation and open space parameters in further experiments. Another difference between the results presented here concerns the investigative factor *building density*. In comparison to the work of (Knöll *et al.* 2018), which found that the building density plays a significant role in stress perception based on the study city of Darmstadt, the factor *building density* shows only a moderate relationship to stress in the study presented here. However, as already explained, the results vary significantly across the five case studies. While case studies K1 and K2 show a strong relationship, no or only a partial relationship between stress and *building density* could be demonstrated in the remaining case studies, as the density in these areas was very homogeneous (see Figure 5). Further research is needed to determine the extent to which the influence of building density on human stress perception may vary in other case studies.

Through the methodological component of *Stressor Unfolding*, the presented research explores an innovative translation methodology for analysing different urban spatial situations. The methodological component of *Stressor Unfolding* aims to transfer complex spatial situations into an abstract coordinate system. However, this abstraction process presents particular challenges. Abstraction involves reducing the representation by deliberately omitting specific spatial features. This reduction becomes particularly apparent in locations where spatial situations are more complex than the classical division into a left and right boundary along a movement path. For example, this occurs in urban public spaces where a building is set back behind large open spaces adjacent to the movement axis and is, therefore, not directly included in the analysed area. Additionally, sharp angles in the movement path may lead to a loss or reduction of information during the unfolding process. This highlights that while the abstract representation of *Stressor Unfolding* enhances comparability, it cannot be entirely dissociated from the spatial context without risking a loss of connection to the specific spatial situation. In this regard, photographic documentation may serve as a valuable complement to the unfolded representations.

Another critical aspect is the integrative nature of the proposed methodological approach. The presented method significantly contributes to an integrative, more holistic analysis of urban spatial problem areas from a human perspective. For the first time, a methodological approach incorporates factual and subjective dimensions of various perception-shaping factors. At the same time, this research acknowledges the fundamental challenge of simplifying complex spatial conditions into an abstract model. Therefore, selecting twelve investigative factors approximates the complex urban research field rather than a finished model. Future research must explore which additional investigative factors and parameters influence human perception of dense urban public spaces and how these factors can be measured. Furthermore, subsequent studies must investigate the stress-related interactions of these factors and their relationships to those already identified.

Another point to discuss concerns the relation to the underlying stress measurements, specifically a possible discrepancy between the stress reactions measured using physiological indicators and the participants' self-assessments. Here, it is likely that not all stress points identified using *Emotion Sensing* measurements are consciously perceived as stressful by the participants. Therefore, a comparison between the subconscious stress reactions measured using physiological indicators and the situations actually consciously perceived as stressful would be interesting for future research. This distinction could impact the stress factors identified here and rearrange or reweight them.

Additionally, there are some limitations due to the aim of using the stress factors identified in the case studies to conclude the usability of these areas for cyclists and pedestrians. Here, the narrow focus of the research design severely limits the interpretation of the results. This is because the research design overlooks some key aspects that may also compromise the usability of the analysed areas. For example, this concerns the connection of urban areas to the overarching transport network, the district's general image, or poor usability for populations with specific needs.

Another limitation arises from the retrospective nature of the causal analysis conducted in this study. It is important to emphasise that the presented research does not conduct any independent *Emotion Sensing* measurements, meaning that the causal analysis in all five case studies happens retrospectively. Within the current setup, conducting both investigations simultaneously is impossible. Consequently, the model cannot fully capture the situation-dependent changes in certain variables. This limitation pertains to factors such as traffic density and perceived sound levels. The retrospective nature of the causal analysis conducted in this study, therefore, only provides a snapshot of the analysed weekdays and times of day, offering an average representation. Building on this challenge, which stems from the differing temporal components of the data collection, questions arise concerning the appropriate scale of spatial analysis. In addition, previous studies have emphasised the importance of accounting for the duration and persistence of physiological impacts. For example, Lederbogen *et al.* (2011) used *functional magnetic resonance imaging (fMRI)* to investigate how urban upbringing and current city living influence neural responses to social stress, revealing that urban upbringing and city living are associated with region-specific changes in stress-related brain activity. A recent study by Dimitrov-Discher *et al.* (2023) linked *fMRI* data from a social stress task to the characteristics of participants' residential street networks in Berlin, using Space Syntax, and highlighted associations between urban street structure and neural stress responses.

Following this, the presented framework must critically examine the general transferability of the methodological approach. A key challenge in this regard is the difficulty of deriving universally valid findings in the intricate fabric of dense urban public spaces. It is essential to acknowledge that the city, as an object of study, cannot be equated with laboratory conditions due to its high complexity and dynamism. Owing to their distinct historical, cultural, and social imprints – their DNA – the findings derived from an analysis of City A cannot be indiscriminately applied to City B. By investigating multiple cities, the proposed approach directly addresses the issue of premature generalisation. Ultimately, these deviations demonstrate that while many aspects can be quantified and generalised, it remains impossible to disregard local specificities when evaluating situations entirely. The overall evaluation of the findings further recognised this issue. Consequently, the study explicitly distances itself from the term correlation, which implies causal relationships and uses the term hypothesis instead. Ultimately, the question remains whether it is even possible to identify demonstrable and transferable causal relationships within the complex research domain of urban perception. Further control trials in new study cities will be necessary to strengthen the formulated hypotheses.

Conclusion and outlook

The present study has developed a novel diagnostic method that delves into human perception of dense urban public spaces through a comprehensive abstraction process. By examining various perception-relevant factors, the proposed approach addresses a subject area that has long remained a Black box in urban research. Beyond qualitative descriptions, this discipline has thus far seen only a few approaches that tackle the elusive, subjective components of the city as an object of study. A key advantage of the developed approach is its ability to integrate both perception and subjective experience, as well as objectively measurable factors. How people perceive an urban public space is not only determined by objectively measurable factors but is also significantly influenced by how comfortable they feel in that space, which determines the practical success of urban planning. Therefore, planners must explore urban public space perception from a human perspective, employing all available means. Based on this requirement, the strong visual and comparative nature of this methodological framework helps not only to consider stress factors individually but also to make initial statements about overarching patterns, thus transferring the results of the individual evaluations back into practice and the real built environment. With these overarching patterns, it is already possible to identify so-called *overarching stress phenomena*, i.e. a critical combination of factors that future urban planning must avoid through targeted efforts. Initial approaches to this, based on the findings of the *Stressor Matrices* obtained here, are outlined in Haug (2025, p. 200 ff). These describe the intersection of movement lines, the overlapping of different spatial demands, the narrowing of movement areas and the location of strong attention magnets as frequently occurring, overarching stress phenomena. This research thus also builds on the work of Jan Gehl, who developed 12 quality criteria for public spaces and summarised them in three main categories: protection, comfort, and enjoyment (Gehl 2010). Fundamentally, both the overarching stress phenomena in this work and Gehl's quality criteria describe, above all, the need to create safe, usable, and aesthetically appealing public spaces for all users in order to ensure high-quality and stress-free urban public spaces.

The approach presented herein facilitates the establishment of multifaceted connections to health outcomes research. The proposed methodological framework offers an innovative approach to examining the extent to which well-being – and, by extension, health – are influenced by environmental factors. In the longer term, this may not only advance the understanding of the underlying determinants of stress but also support more comprehensive investigations into associated health diseases, including, for example, cardiovascular diseases, metabolic disorders, and mental illnesses.

In addition to the broad range of investigative factors, the proposed approach also pioneers a novel methodological mix, combining the analysis of two-dimensional data sources, three-dimensional remote analyses of imagery, and on-site inspections. With the newly introduced methodological components of *Stressor Unfolding* and *Stressor Matrix*, it is now possible to translate the findings from these analyses – despite their vast content and methodological variations – into a comparable format. Finally, combining *Stressor Unfoldings* with the stress measurements results identified six common stressors across five case studies: *shopfront zones, public space elements, street space organisation, traffic, parking*, and *acoustics*.

While the current study provides valuable insights, it also opens up new questions for future research.

This approach is based on detecting stress hotspots using *Emotion Sensing* measurements, which utilise physiological indicators such as skin conductance and skin temperature to identify stress reactions in the human body. Follow-up research could experiment with various other physiological indicators and measurement settings (see section 1.2.1.). This also opens up another exciting avenue of research: experimenting with the detection of the opposite emotional state, namely, positive emotions and thus the detection of feel-good places in real-world urban environments. Here, for example, the *blenderFace method* – an optical measurement technique that detects the mimic processing of emotions based on the smallest movements of the facial skin – offers promising starting points (Zinkernagel *et al.* 2019). This method could be on the rise in the context of cycling, as video recordings of the participating test subjects can be made relatively easily by attaching a camera to their helmets. The combination of the detection of feel-good places with the presented methodological approach could then make it possible to identify 'feel-good factors' that positively influence human perception of urban spaces.

The presented methodological approach establishes several key connections to planning practice. Further development – especially in digital public services and the design of mobility-oriented, livable urban public spaces – could provide valuable support for municipal planning. In this context, the method could evolve into a planning tool that can help to evaluate existing urban public spaces and provide a holistic overview for monitoring transformation processes. Looking ahead, this tool could be used both within formal and informal planning processes. Its applications range from planning assistance for specific cycling infrastructure projects to monitoring transformation processes and supporting participatory processes. Clarifying the various investigative factors in the *Stressor Matrices* offers added value. This is especially crucial in urban transformation tasks when comparing an existing situation with different planning alternatives.

Methodologically, the interfaces in this context primarily lie in combining the tool with municipal 3D city models or digital twins. These virtual 3D city models are widely used in cities to aggregate and visualise information. However, what is crucial is that the data within these digital twins are stored and applied effectively in municipal planning, in line with digital public services, to assess the impacts of individual measures and transformation processes. In this regard, the intelligent linking of various datasets and systems is key to deriving insights from the digital model for the respective planning processes. The presented method could, as with the *Smart City Platform* proposed by Ruohomäki *et al.* (2018), serve as a complement to bring urban digital twins a step closer to a *system of systems* (Fraunhofer 2023). In this context, the presented approach could enhance the digital twin with a tool that enables an assessment of the urban public space from a human perspective. More holistic planning would allow for the analysis of a broad range of environmental factors directly from the model's data and enable a crucial shift in perspective for the digital planning of real, human-centric urban public spaces.

Furthermore, a key challenge in implementing the methodology will be its systematisation and automation. In this context, it is important to implement automated image analysis of street views generated by the digital twin. In this field, some research studies have already demonstrated the analysis of real-world environments by evaluating street-level imagery (Seiferling *et al.* 2017, Aravena Pelizari *et al.* 2021). This means that in further developing the presented methodology, a digital recording system could automatically identify and categorise the corresponding objects using machine learning based on specific training data related to the factors under investigation and their associated subparameters. In the long term, this machine-based object recognition could enable the direct input of the identified characteristics into the stressor progression.

This summary makes it clear: The developed method represents – despite certain limitations – an important step towards investigating the causes of urban stress phenomena in dense urban and street spaces.

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No potential conflict of interest was reported by the author(s).

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