Extending the dimensions of personal exposure assessment: A methodological discussion on perceived and measured noise and air pollution in traffic

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Published as:

Marquart, H., et al. (2021). "Extending the dimensions of personal exposure assessment: A methodological discussion on perceived and measured noise and air pollution in traffic." Journal of Transport Geography **93**: 103085. https://doi.org/10.1016/j.jtrangeo.2021.103085

Abstract

Background
The exposure to air pollution and noise is severely impacting people's health and is especially high alongside urban road- and rail-traffic. In traditional exposure research, air pollution and noise are monitored with stationary measurement devices or based on models. During the last years, mobile measurement techniques with GPS-tracking have increased. Moreover, studies have investigated another dimension of personal exposure: the perceived exposure.

Aim
Most of these studies make use of quantitative methods such as surveys, complemented by stationary or wearable sensors. Little research exist that applies qualitative methods to examine how people experience and perceive exposure on-the-move, contrasting it to actual measurements. The aim of this paper is to discuss the potential of a novel method, which extends the dimensions of personal exposure by including the situational context of exposure perception.

Methods/Case study
Firstly, different methods for exposure research are presented. Secondly, we introduce a novel mixed-method approach, exploring cyclists and pedestrians perceived and measured exposure on-the-move by combining mobile interviews (Go-/Ride-Alongs) and wearable sensors. We will present the methodological findings using a case study and have a quantitative method (smartphone questionnaire, wearable sensors) as a reference.

Results and discussion
The differences of perceived and measured exposure, proven through the reference method, are a result of different situational contexts as shown by the mobile interviews (knowledge, embodied experience, life situation, activities). The methodological findings show, that mobile methods complemented by wearables introduce new dimensions of personal exposure: they shed light on the situational contexts that affect exposure perception during commute.

Conclusion
We argue that both, perceived and measured exposure to air pollution and noise, need to be considered simultaneously. Complementing mobile interviews or surveys with wearable sensor data improves the understanding of urban dwellers requirements for healthier mobility. Potentials of these methods should be investigated further, both in research and for supporting urban transport planning decisions adapted to people's needs.

Keywords: mobile interview, wearable sensors, mixed-methods, air pollution, noise, perception

1. Introduction

Environmental stressors, such as air pollution and noise, have traditionally been studied in environmental exposure research. Especially urban dwellers' personal exposure has received great attention, both regarding exposure indoors or personal exposure in urban traffic (Schlink & Ueberham, 2020; Steinle et al., 2013). The methods applied have increased with new technological developments such as wearable sensors and GPS-tracking, which do not rely on static monitoring, but provide measurements on the person and on-the-move (Larkin & Hystad, 2017; Schlink & Ueberham, 2020; Snyder et al., 2013; Steinle et al., 2013). Investigating people's exposure or health impacts of dynamic environmental situations in urban traffic is also of interest for health and transport research (Chaix, 2018; Engström & Forsberg, 2019; McNabola et al., 2008). Monitoring exposure is crucial, because modern-day ambient air pollutants are causing severe health effects as well as psychological distress, mood changes and mental disorders (Alotaibi et al., 2019; Howell et al., 2019; Kelly & Fussell, 2015; Künzli et al., 2000; Li et al., 2018; Lin et al., 2019; Sass et al., 2017; Sears et al., 2018). Moreover, the burden of disease from environmental noise is discussed to be the second highest after air pollution (Hänninen et al. 2014; WHO, 2018). The exposure to high (above 70 dB(A)) noise levels over a longer period of time can result in physical health impacts and psychological distress (Eriksson et al., 2018; Stallen, 1999; WHO, 2018)

Next to physical health impacts, people's perception of noise and air pollution has an impact on mobility decisions, perceived health and wellbeing and overall quality of life (Cori, et al., 2020; Gössling et al., 2019; Li & Zhou, 2020; Orru et al., 2018). Recently, studies have investigated this exposure dimension: the perceived exposure (Cori et al., 2020; Gössling et al., 2019; Martens et al., 2018; Nikolopoulou et al., 2011). Monitored exposure levels were complemented by recordings of people's perceptions, showing that perceived and measured exposure can differ (de Souza et al., 2020; Gössling et al., 2019;; Johnson, 2012; Kou et al. 2020; Nikolopoulou et al., 2011; Ueberham et al., 2019; Verbeek, 2018). This calls for a need to investigate the reasons for this discrepancy and people's perceptions regarding air pollution and noise. As for policy and planning, knowing the perceived exposure in urban traffic is important for improving urban dweller's perceived health, overall wellbeing and satisfaction of travel.

Following the "new mobilities paradigm" and "politics of mobility", travel and transport has long been looked at from "sedentarist" theories, without considering the mobilities, the practices and representations, which are embodied in the individual while moving (Cresswell, 2010; Sheller & Urry, 2006). Practiced mobility is experienced through the body, thus, individual's embodied experiences and perceptions should be recognized (Cresswell, 2010; van Duppen & Spierings, 2013). Studies which draw on this paradigm make use of mobile methods (Büscher, 2011; Hein et al., 2008). With mobile methods various exposure situations can be recorded, but also the spatio-temporal and the contextual information of exposure. These human geo-sensing approaches make use of "people as sensors": urban dwellers record geo-located information on environmental conditions or their perceptions using mobile technology – integrating humans, technology and the environment (Sagl et al., 2015; Zeile et al., 2016). Thus far, most mobile exposure studies use quantitative methods and measure the actual exposure, its impact on health or allow people evaluate the extent to which they feel exposed. This is important for statistical analysis and basis for decision-making. However, reasons for the evaluation of exposure and its impact on wellbeing and mobility behavior can only partly be explained. Exploring experiences and practices while moving, which shape the exposure perception, are important to comprehensively understand personal exposure. Qualitative mobile methods are beneficial, yet, they are rarely used for researching exposure.

We close this research gap by presenting a novel mixed-methods approach: combining qualitative mobile interviews by bicycle / on foot (i.e in public transport) with simultaneously measuring air pollution and noise with wearable sensors on-the-move. Thereby, we raise the question what to consider when talking about "personal exposure" in traffic. Is it the objectively measured exposure, recorded by sensors, the subjectively perceived exposure, documented by surveys/interviews or a combination of both, using mixed-methods approaches? Taking a second method with quantitative surveys and wearables as a reference, we discuss the benefits and findings of our novel mixed-methods approach. Hence, we further introduce the situational context, in which moving urban dwellers experience exposure: their practices and activities, embodied experiences, knowledge and life situation. By discussing the methods, we extend the personal exposure dimensions by addressing not only the measured and perceived exposure, but also the situational context.

Firstly, this paper sheds light on methods for researching measured and perceived exposure, both stationary and on person/en-route, and discuss their implementation. Secondly, two mixed-method approaches combining wearables with mobile interviews ((Method 1) smartphone-based and (Method 2) Go-/Ride-Alongs) are presented and strength and weaknesses are discussed. The focus lies on the latter approach (Method 2) and its potential for transport and exposure research. Finally, our findings lead to the development of extended personal exposure dimensions, as discussed in chapter 4.

2. State of research: methods in personal exposure research

Exposure research has undergone some fundamental changes in recent years and displays a wide field of aims and monitoring methods (Fig. 1) (Larkin & Hystad, 2017; Snyder et al., 2013). Next to objective measurements or models, the subjective perceptions have received attention. Usually, subjective perceptions have been captured stationary through quantitative methods (2.1) or qualitative methods (2.3). Recently, emerging technologies such as GPS and wearable sensors made it possible to record on-the-move. Moving individuals can record perceptions using quantitative methods (2.2). Others have used qualitative mobile methods (2.4). In the following, we will elaborate these mixed-method studies with an emphasize on the still underrepresented field of qualitative exposure studies (Fig. 1).

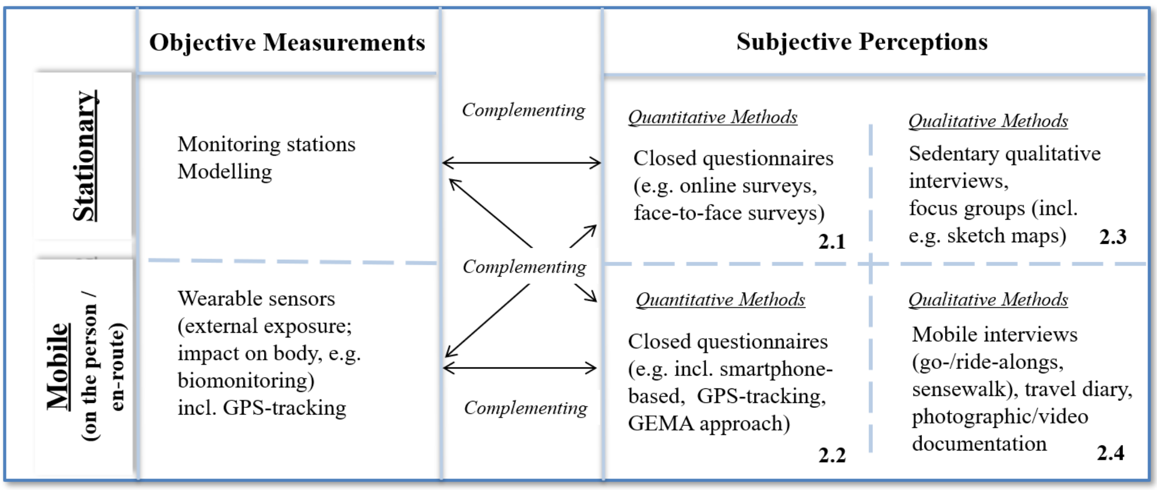

Figure 1 Overview of different methods for researching the exposure to environmental stressors in the city. The methods can be applied complementary. The numbers relate to the respective chapter.

2.1 Stationary measurements and quantitative methods

Exposure research using stationary measurements or modelled levels of pollution have recently complementary used closed questionnaires. They statistically explore relations of city-wide measured/modelled exposure data and subjectively perceived exposure. Reames and Bravo (2019) and Dons et al. (2018) used community (e.g. Europe-/nation-wide) air quality data and compared it to public perception and health concerns, one finding that high level of NO2 was associated with concern, but PM2.5 was not (Dons et al., 2018). King's (2015) study used air quality data compared to people's evaluation of neighborhoods. They argue that qualitative research is needed to better understand individual-level exposure. Nikolopoulou et al. (2011) investigated that perceived poor air quality is in line with higher PM concentrations, using field surveys, compared to locally measured air quality and noise monitoring. Modig and Forsberg (2007) proved an increase in annoyance due to rising exhaust fume levels, using modelled levels of NO2 and questionnaires. Noise perception (questionnaire-based) was in line with measured noise levels (stationary measurements/maps), however, the discomfort of residents is rarely addressed (Camusso & Pronello, 2016; von Szombathely et al., 2018). Verbeek (2018) applied questionnaires on annoyance, exposure and health concerns with urban noise maps and related noise models, showing that their relation is weak. Bartels et al. (2015) used stationary noise measurements for aircraft noise and compared them with annoyance rating using closed questionnaires, showing that non-acoustical factors such as situational and personal factors (e.g. time of the day, activity) have a considerable impact on evaluated noise annoyance. Heat perception compared to stationary measurements was conducted by Franck et al., (2013), showing that subjective feeling did not clearly reflect measured data. These studies apply city-wide modelled or stationary measurements. For exploring dynamic exposure situations, mobile methods are needed.

2.2 Mobile measurement and quantitative methods

Collecting exposure data has shifted from solely relying on complex, stationary measurement devices to the additional usage of mobile/wearable sensors (Snyder et al., 2013). These technologies have "revolutionized" personal exposure research (Larkin & Hystad, 2017). The exposure assessment of moving urban dwellers requires a flexible approach due to varying exposure situations: carrying sensors on the body is beneficial to understand the spatiotemporal microenvironments of people on-the-move (Carreras et al., 2020; Ma et al. 2020; Nieuwenhuijsen, 2016; Ueberham & Schlink, 2018). As shown in a study from China, collecting person-specific real-time air pollution data with wearable sensors supports the understanding of the spatiotemporal microenvironments of people, the effect of different pollution sources during daily activities and the influence of their adopted protective actions (Ma et al. 2020).

To simultaneously document people's perceptions, some studies have applied closed questionnaires complementary to wearable sensors. Mila et al. (2018) monitored personal exposure data (PM2.5) on-the-move integrated with a questionnaire, a camera and GPS in periurban India. Other studies used wearable air pollution sensors (Leaffer et al., 2019) or multiple wearable exposure measurements (Ueberham et al., 2019) combined with smartphone-app questionnaires. In-vehicle monitoring of PM and black carbon was applied by Gany et al. (2017), comparing it to driver's knowledge, attitudes and beliefs. Smartphones are beneficial for collecting a large amount of data about people's perceptions on-the-move (Klettner et al., 2013). Approaches of geographic ecological momentary assessment (GEMA) often make use of smartphones by repeatedly sending participants questionnaires on their real-time perceptions, feelings, emotions, behavior and stress levels combined with GPS data (Kou et al. 2020). Two recent studies made use of these time-geographic approaches by applying a GEMA to assess people's momentary objectively measured noise, momentary perceived noise and psychological distress on-the-move combining it with travel-diaries to understand effects of activity on perceived and measured noise (Kou et al. 2020; Zhang et al. 2020). They examined, that differences in perceived and measured noise are affected by the context of the activity (Kou et al. 2020). Closed questionnaires, especially combined with GPS-tracking, are valuable for comparing questionnaire answers with mobile measurements and provide information on participants' activities or places in which measurements were taken and perceptions documented (Zhang et al. 2020; Kou et al. 2020). Therefore, the situational context of exposure perception and differences in perceived and measured exposure can be captured to a certain extend. However, they do not give insights into people's perceptions in-depth or provide the possibility to discuss ad-hoc behavior.

2.3 Stationary measurements and qualitative methods

Some studies display no clear evidence that the perceived environment is in line with the measured data (e.g. de Souza et al., 2020; Johnson, 2012; Kou et al. 2020; Lenzholzer et al., 2018; Ueberham et al., 2019). Qualitative methods are helpful to understand these differences. They explore experiences and context of a behavior, more than studying "at the surface" with closed questions (Bickerstaff & Walker, 2001). Especially mixed-methods approaches help to research the human-environment relationship, environmental exposure and wellbeing (King, 2015; Kuckartz, 2014; Steinmetz-Wood et al., 2019). Only few studies have combined stationary qualitative methods with measurements of the immediate environment. Among them Szeremeta and Zannin (2009), who have investigated the soundscape and related environmental factors through stationary open-ended questionnaires in comparison with measurements. Haddad and de Nazelle (2018) tested the impact of air pollution sensors and smartphone apps on travel behavior, using pre- and post-in-depth interviews. Cortesão et al. (2020) complemented observations, spatially localized interviews and photographic comparisons with microclimatic measurements (portable). However, stationary qualitative methods are limited to the remembered situation or general perceptions. They cannot give insights into ad-hoc behavior or in-situ perceptions.

2.4 Mobile measurements and qualitative methods

Mobile qualitative methods can address this issue. They explore people's perceptions and experiences in-depths while moving, e.g. recorded audio open-ended questions related to wellbeing and nature (Doherty et al., 2014), travel diaries to examine the activities during exposure (Kou et al.2020), geo-narratives incorporating space-time trajectories of people and narratives of daily life experiences (Kwan & Ding, 2008) or thermal walks to explore thermo-spatial perception on-site (Lenzholzer et al., 2018). These methods are valuable to explore perceptions and activities on-site without necessarily having an interviewer present. To dive deeper into people's experiences, practices and perceptions, however, it can be valuable to apply mobile qualitative interview approaches.

Mobile qualitative interviews (Walking Interviews or Go-/Ride-Alongs) address the spatial limits of sedentary, post-hoc qualitative interviews. They use the background of field observations and draw attention to the immediate lived-space (Carpiano, 2009; Evans & Jones, 2011; Kusenbach, 2003). It is a form of qualitative interview conducted while an interviewer accompanies the interviewee (Carpiano, 2009; King & Woodroffe, 2017). In Go-/Ride-Along studies, the movement itself becomes part of the research: the researcher can experience the space of the studied subject him-/herself (Hein et al., 2008). Moreover, moving together at the interviewees' typical route/time gives insights into interviewee's practices, routes choices and perceptions of space and makes it possible discuss them on-site (Hein et al., 2008; Kusenbach, 2003). These spatially-related qualitative data gathered through mobile interviews demands for "qualitative GIS" (geographic information systems), supporting a visualization and analysis of complex interactions among space and people's experiences (Kwan & Ding, 2008).

Go-/Ride-Along studies investigated participants' relation to place (Hitchings & Jones, 2004; Hodgson, 2012), their experiences and perceptions of their environment (Boettge et al., 2017; Kelly, et al., 2011; Kusenbach, 2003; Lenzholzer et al., 2018) or promote a narrative about a specific topic, e.g. food security (King & Woodroffe, 2017), everyday travel (Hodgson, 2012; Pooley et al., 2013; Pooley et al., 2011; van Duppen & Spierings, 2013), health perception (Carpiano, 2009; Garcia et al., 2012) or physical experience (Spinney, 2016). However, there is hardly any research which combines Go-/Ride-

Alongs with measured exposure data, except from our pilot study testing this method (Marquart et al. 2021).

3 Applying the methods: perceived and measured exposure on-the-move

We will now provide insights into our novel mixed-methods approach (Method 2), using a precedent multiple exposure study (Method 1) as a reference for discussion. Both studies explore measured and perceived exposure on-the-move using quantitative (Method 1) and qualitative (Method 2) approaches and similar wearable sensors, therefore, they are suitable to compare. The reference study (Method 1), an already conducted study by Ueberham et al. (2019), applied smartphone-based questionnaires and wearable sensors. The novel study (Method 2) applied Go-/Ride-Alongs in combination with wearable sensors. We will present both methods and discuss the methodological findings and our experiences of the second method.

3.1 Method 1: smartphone survey and mobile measurements (reference method)

For personal exposure assessments it is of high interest to capture as many influencing factors as possible to characterize the individual's exposure. Therefore, both objective and subjective data are crucial to create a broader picture of multiple environmental and psycho-social influences. For one of our own explorative studies with cyclists, we designed an open-source smartphone application, in which all participants entered their own perceptions of multiple parameters (perceived air pollution, perceived noise exposure and burden from heat). These pop-up questions appeared after each cycle route, when the trip was finished, with a button on the home screen. The participants (n=66) rated their individual exposure on ordinal scales. Additionally, two text fields were used to specify the purpose of the trip and to mention possible detours (Ueberham et al., 2019). The subjective data was stored together with the sensor data of the smartphone (noise, GPS, light level). Simultaneously, particle number counts of particulate matter (0.5-2.5µm) where collected using a wearable sensor. All details can be found in Ueberham et al. (2018).

An advantage of the joint measurement approach is that the subjective data can be compared more easily with objective data by standard statistical techniques (e.g. correlations, regressions, significance tests). Referring to the results of Ueberham et al. (2019), noise exposure is highly different in terms of objective values and subjective perception. The main disadvantage of this approach is that the reasons for differences cannot be explained. Therefore, qualitative mixed methods have to be applied, ideally by accompanying interviewees to ask for detailed feedback on exposure perceptions.

3.2 Method 2: Go-/Ride-Along and mobile measurements (case study)

In this study interviewees were accompanied by an interviewer using Go-/Ride-Alongs, complemented by wearable sensors. The aim was to explore how people perceive air and noise pollution on their daily way from work to home and discover reasons for discrepancies of perceived and measured exposure. Our sample comprised 10 people living and commuting from work to home in Berlin, Germany (Appendix 1). They used bicycle or public transport (i.e. including walking), transport modes known to be highest exposed (Okokon et al., 2017). The interviews took place in October/November 2019. The interviewees could choose day (workday) and time (after work).

Firstly, sedentary pre-interviews were conducted. These interviews served a.) as a basis for the mobile interview, thus, the interviewer was already prepared for specific aspects and routes, b.) the interviewee could get familiar with the situation, which made the subsequent ride/walk together more confident and c.) already stimulated a narrative about mobility and exposure perception (Finlay & Bowman, 2017). After the introductory interview, the interviewee was accompanied on his/her way from work to home, by foot (incl. public transport) or bicycle. Meanwhile, a semi-structured questionnaire covered four topics: (1) mobility behavior and actions, (2) perceptions of the immediate environment (visual, olfactory, auditory), including air and noise pollution, (3) health perception and situative wellbeing and (4) authority arguments, aiming at confronting the interviewee with information about air and noise pollution in-situ. Based on qualitative interview procedures (Przyborski & Wohlrab-Sahr, 2014), the mobile interviews started with open and unspecific questions (e.g. *How do you perceive your environment at the moment? What do you hear, smell, see?; Why do we take this route?; How are you feeling at the moment regarding your environment?*), got more specific during the mobile interview (e.g. *You have talked about how you [don't] like [the noise/air], how would you translate ['don't] like', what does it do to you physically or mentally?*) and directly pointed at specific aspects in the later stages of the interview, e.g. using authority arguments (*Have you known, that noise over 55 dB(A) is already impacting your health according to the WHO? Usually streets with a high traffic volume exceed even 70 dB(A); We have now [referring to the display of the particle number counter] particles, that is translated in bad air quality, compared to [street XY] before*.) (Appendix 2). Meanwhile, specific actions (e.g. sudden route changes or choices) or situations (dangerous, loud, heavy traffic, greenery) demanded for flexible adaptations of the semi-structured questions or for ad-hoc questions. This ensured that all topics were covered while new and unexpected aspects could be discussed. The interviews were recorded with microphones attached to each person. Thirdly, the interviewer carried wearable sensors (based on Ueberham et al. 2019) measuring noise (dB(A), interval: 2s), particle number counts (PNC) from 0.5-2.5µm, #/ft^3 (interval: 1min), and GPS. The study by Ueberham and Schlink (2018) presents a rigorous evaluation of the accuracy and reliability of the sensors utilized in the present study. Pictures were taken by the interviewer during or after the interview.

The mobile interviews were transcribed (software f4), including time stamps. Using qualitative content analysis (QCA), the transcripts were coded and analysed using MaxQDA 2020. The measurements were merged and analysed using QGIS 3.10.3. Both quantitative and qualitative data were combined in several phases of the research process (Fig. 2) (Kuckartz, 2014; Steinmetz-Wood et al., 2019). We used two strategies for mixed-methods analysis: comparison and assimilation (Steinmetz-Wood et al., 2019). To understand the relation of perceived and measured exposure on-site, the qualitative and measured data were compared through assimilating the qualitative data to value-oriented codes (e.g. unpleasant, pleasant, relaxing, stressful). For better interpretation of the PNC values along one route and comparison between the participants, the PNC numbers for each route were divided into seven quantiles, where "7" is extremely high and "1" is extremely low. Moreover, to investigate divergences and similarities, we incorporated interpretations derived from the qualitative data (transcripts and interviewer's observations) and land-use data (green and blue spaces[1]). Additionally, site-specific statements and behaviour were analysed and complemented by the measurements, supporting an interpretation of the qualitative data.

[1] Geoportal Berlin/FNP (Flächennutzungsplan Berlin), https://fbinter.stadt-berlin.de/fb/index.jsp, dl-de/by-2-0

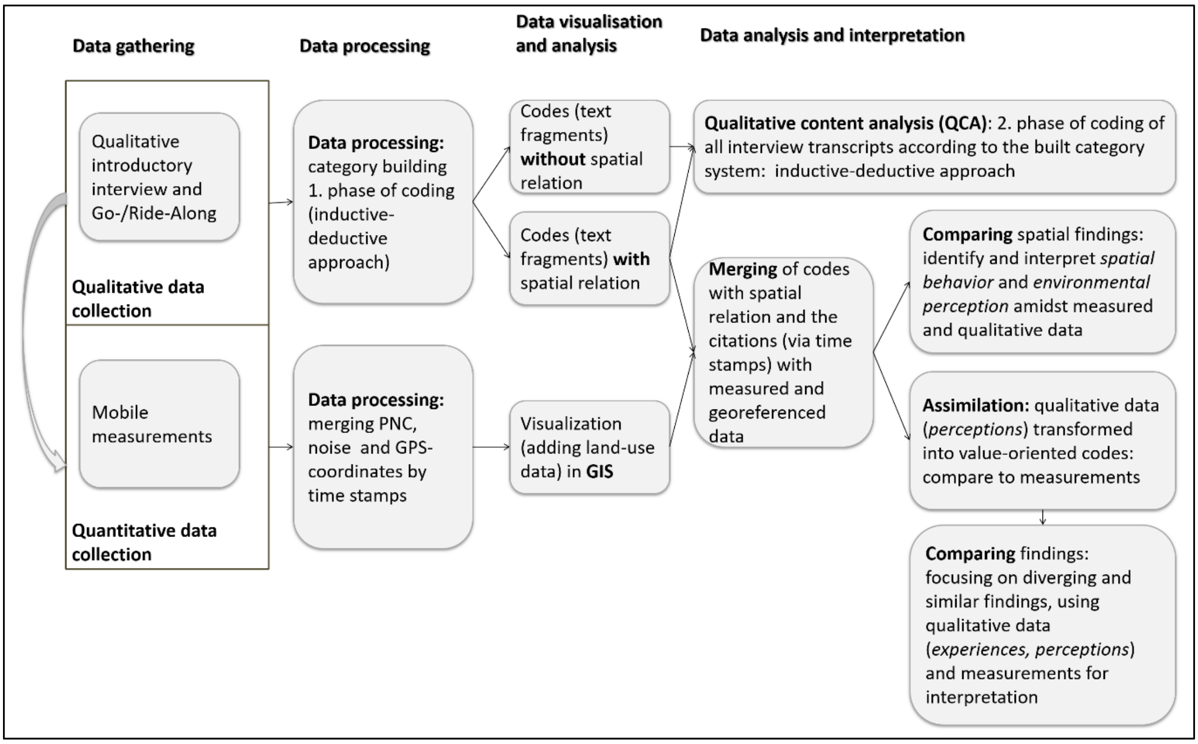

Figure 2: Research design and data analysis procedure using an integrated mixed-method approach. This article specifically focuses on the data (codes and measured data) with spatial relation.

4. Methodological findings

The focus of this article is on the methodological findings and possibilities of the mixed-methods approach (Method 2). We will primarily draw attention to the spatial findings, which lead to the development of extended personal exposure dimensions (chapter 5.2).

We analyzed and compared the measured data, the interviewer's observations and the perceived exposure reported by the interviewees on-the-move. Applying this method does not only highlight differences or similarities of perceived and measured exposure, we could also reveal reasons behind these discrepancies. Our findings show that exposure perceptions, perceived health and wellbeing relies on individuals' embodied experiences, e.g. pleasant smells of nature or scenery/visual experiences, their knowledge of the route and affective/emotional experiences, which are related to imminent/past activities or life situations. We will elaborate these findings in the following.

The external situation, which could be documented in-situ, was crucial for exposure evaluation: sudden situations causing upset and being perceived as unpleasant were most often stated in relation to noticeable air pollution, but also in relation to stressful noise. The interviewees often pointed at sudden incidents and environmental cues, which impacted how they perceive air and noise pollution at the moment:

> "*Sometimes I am angry, so I think, why is it like that? Why is it possible, why is it allowed in the first place? Because it affects so many people. Do you feel it? Now? [**points at the cars**] That is what I meant when I said that this area is especially intense. […] Yes, [the smell], and also in my throat somehow...*" (RA1[2]) (noise: 63 dB(A), PNC: 7 - comparably extremely high)).
>
> *"In any case, it's the long waiting here [**loud car is passing by**] And yes [**points at the car**] Noise, yes, I think that's bad! […] This artificial noise is becoming more and more present. […]*

[2] RA[number] refers to „Ride-Along"[participant number], GA refers to "Go-Along" (i.e. public transport users)

if I ride by myself, I am lost in my thoughts or with headphones." (RA3) (noise: 67-69 dB(A), PNC: 7 - comparably extremely high).

Environmental cues, such as the sight of cars, exhaust fumes, the sound of a loud car or an ambulance (*"Well, there is a lot going on here [**points at the loud sirens of an ambulance**] […] It is not a real relaxation."* (RA7)), influenced the perception of space and stimulated a narrative about it. These were partly in line with the measurements. Moreover, asking about wellbeing in the very moment supported the interviewee to consider carefully how their immediate environment impacted them, going further than environmental cues. For example, knowledge was an important aspect for exposure evaluation and wellbeing. Route sections were perceived as positive, if interviewees knew that routes "*a whole lot worse*" (RA7) are coming ahead (e.g. Fig 4) or knowing that certain route sections helped to "*recharge the batteries and soak up the peace and quiet*" (RA10). We could show that this is in line with comparably lower air and noise pollution levels, supported by greenery and less car traffic (e.g. RA10).

However, the wearable sensors displayed that positive evaluation of the environment was not always in line with measured noise data, showing that route sections with high noise levels of 67-75 dB(A) could also be evaluated as pleasant. This can be a result of the embodied experience (visual and olfactory) of the interviewee, which is caused by the immediate environmental situation (Fig. 3).

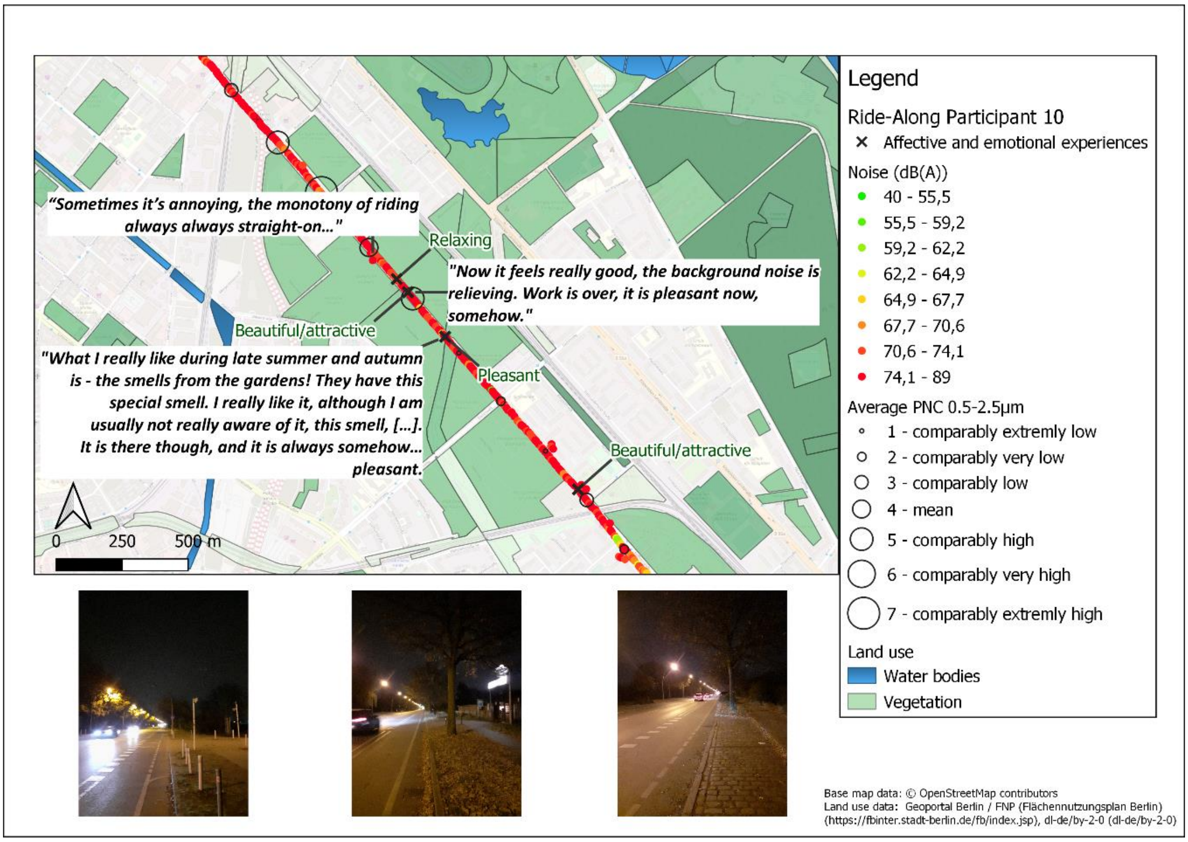

Figure 3: Ride-Along on an arterial road with high noise pollution and low air pollution, contrasting the statements of the interviewee who perceives the environment as pleasant and attractive (pictures taken afterwards).

Additionally, positively perceived sounds have an impact on positive experiences along the route, which can be explored by accompanying the interviewee. Three pedestrians reported sounds from musicians in the subway as pleasant, not necessarily in line with measured high noise levels at the respective moments (GA4, GA6, GA8):

> *"This music, for example, [**points at the musicians in the subway hall**], I know them from other stations, they are cool, I like them."* (GA4) (noise: 69-77 dB(A); PNC: 4 – mean)

Next to high noise levels, comparably high air-polluted route sections could be evaluated as positive, because the urban aesthetics (2-times) and shops or entertainment along the route (2-times) resulted in evaluations such as beautiful/attractive (GA6, GA8). The knowledge that less attractive route-sections are coming ahead also positively influences the mobility and exposure experience (Fig. 4).

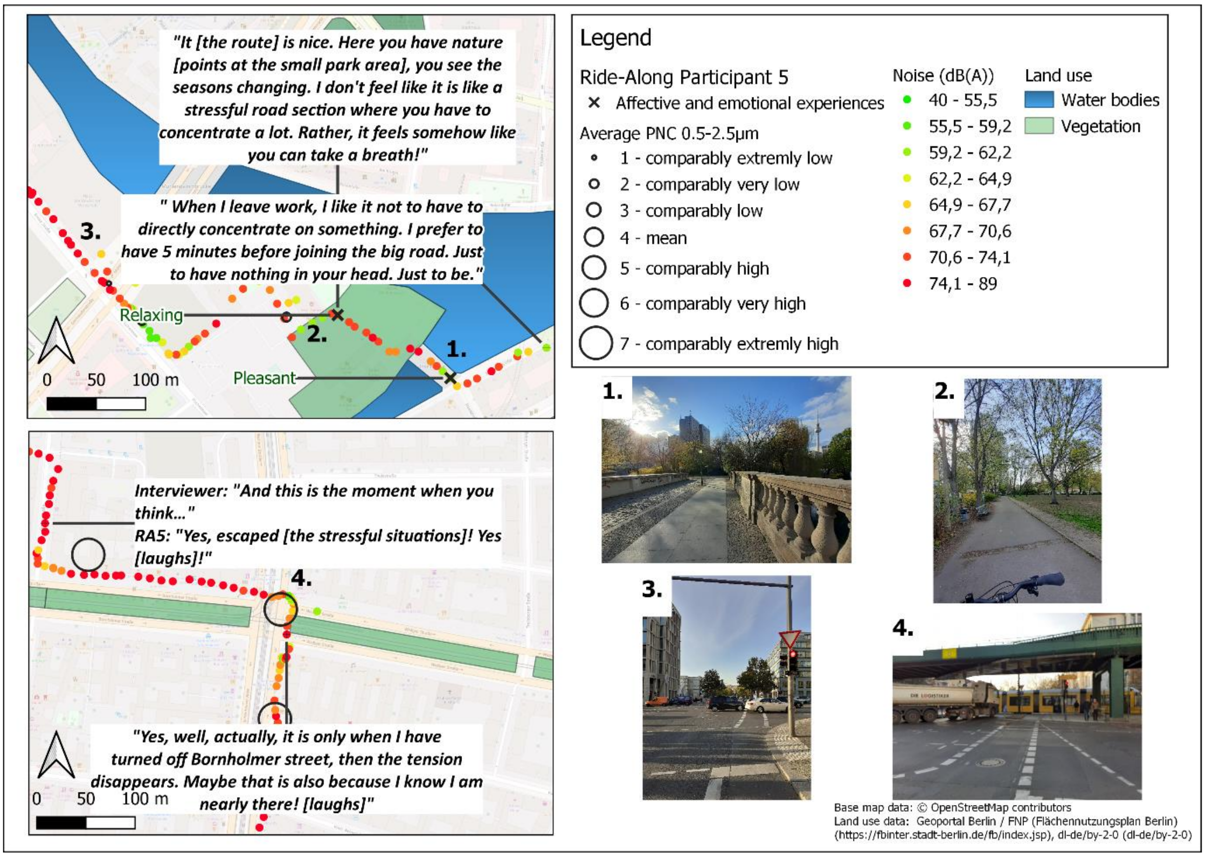

Figure 4: Example of the importance of contextual information aligning with measured exposure: Greenery and blue space (map above) are evaluated positively, especially in comparison with the "big road" coming ahead. PNC is comparably low. At a main intersection with comparably high PNC and noise levels (map below), the interviewee evaluated the environment as unpleasant, but states that the tension disappears because he/she is nearly home. (picture 1-2 taken afterwards, picture 3-4 taken during the ride-along).

The importance of previous/upcoming activities and life situations were shown in many statements close to the work place or close to home (Fig. 4): when asking ad-hoc in this situation, most interviewees said that they feel good, leaving their workplace behind or positively evaluated their environment close to home (e.g. "*I am certainly happy that I have arrived and am released*" (RA1), "*Here it is always nice, I know, I will be home soon.*" (RA7)). Positive memories with a certain area/smell/sight could be discovered when asking ad-hoc in the situation (e.g. tram passing) ("*I like hearing the sound of the tramway. […] It reminds me of my home town.*" (GA6)). Reasons behind sudden route choices could be asked ad-hoc: Interviewees reported about their knowledge of short-cuts and the importance of knowing hidden side-roads, most of them measured less air pollution and noise comparing to the main roads (RA 1, RA2, RA3, RA5, RA7, GA8, RA10). This could be asked directly while the interviewee took the short-cut or "hidden" side-road.

5. Discussion

In this paper we discussed methods for researching personal exposure to air pollution and noise and presented a mobile qualitative and a mobile quantitative approach, which are complemented by wearable sensors. It is argued that bicycle and public transport are underrepresented in research using mobile interview methods (Finlay & Bowman, 2017). The presented mixed-method approaches provide in-depth insights into cyclists and public transport users commute and consider the importance of mobile methods next to sedentarist theories (Büscher, 2011; Sheller & Urry, 2006).

5.1 Strength and weaknesses mobile interviews (Method 2) and surveys (Method 1)

Interviewing while moving (Method 2) sheds light on reasons for route choices and the perceived immediate environment. While other approaches, such as mental maps or qualitative post-hoc interviews, can also draw attention to these topics (Boschmann & Cubbon, 2014; Marquart et al., 2020; Stefansdottir, 2014), accompanying a person can reveal aspects which the interviewees may not mention beforehand and help to better reflect his/her route choices, experiences and perceptions in-situ (chapter 3.2). Other mobile methods, such as travel diaries or geographic ecological momentary assessments (GEMA), are also methods for gathering spatial perceptions, behaviour and the situational context of people on-the-move (Zhang et al. 2020; Kou et al. 2021). However, they can only capture behaviour, perceptions and the situational context to some extent. Mobile interview methods, derived from "mobile ethnography", are important in the "new mobilities paradigm" to deeply engage in people's mobilities, understand their practice of movement and how mobility is experienced through the body in various situations (Cresswell, 2010; Sheller & Urry, 2006). Our results are in line with van Duppen & Spiering's (2013) Ride-Alongs, who gives insights into diverse urban sensescapes, embodied experiences and mobility tactics (e.g. shortcuts or behavior in traffic) of cyclists. Sudden incidents (e.g. appearance of an ambulance, appearance of musicians) or stimulating questions (*How do you perceive your environment at the moment? What do you hear, smell, see?*) help to explore how the commute is experienced. The interviewees were sometimes surprised about their behaviour (RA2: "*Yes, this is indeed a route I take to avoid the construction site!*"). In comparison with other methods for exploring exposure on-the-move (chapter 2), mobile interview methods are especially interesting for investigating and discussing momentary perceptions, embodied experiences and mobility behaviour in-depths. Complementing mobile interviews with wearable sensor data and photographs supports the interpretation of the qualitative data and its situational context.

We also experienced limitations with this method. It can be difficult to keep the interview situation in high traffic volume streets by bicycle or in crowded trains. Moreover, safety is an important aspect which has to be critically considered (Finlay & Bowman, 2017). We aimed at addressing this by giving a microphone to the interviewee and interviewer, hence, we do not necessarily need to be next to each other all time (Kusenbach, 2003). In crowded or very empty (i.e. silent) trains, the interviewees seemed uncomfortable to be interviewed in front of others. This hindered a normal interview conversation, since this "contrived social situation" can disturb the "natural" situation that the interview is trying to capture (Kusenbach, 2003). Moreover, the presence of the interviewer could result in a perceived power imbalance and the questions raised can influence perceptions and interpretations (Hein et al., 2008; King & Woodroffe, 2017; Kusenbach, 2003). However, the introductory pre-interview in a Café, i.e. neutral surrounding, supported a less contrived situation (Kusenbach, 2003). Interviewing while moving together might also create new experiences and a new consideration of the situational context, which we consider as particular interesting and further investigated during the interview. For more discussion about that see i.a. Hein et al., (2008), Kowalewski & Bartłomiejski (2020) and Marquart et al. (2021). Finally, the nature of qualitative data does not allow for conclusions in statistical terms and cannot be statistically compared to one another or the sensor data.

The smartphone-based survey and wearable sensors (Method 1) shed light on quantitative data of a greater sample, thus, providing the statistical evidences which are missing in qualitative approaches. The main limitation of using smartphones as a tool to record subjective data is the time and effort of the study participants to enter their perceptions. Especially during mobile measurements or exposure recording on-the-move it is of high importance to ensure an easy and fast way of collecting subjective data. Complicated or long-lasting queries on the smartphone can lower the motivation of the participants with negative effects on compliance or non-reflective reporting. Having this in mind, the most effective way of using smartphones for subjective exposure data collection are quantitative and mostly closed questions.

Both methods are valuable for researching perceived and measured exposure on-the-move. In both cases, the wearable sensors give information about the external situation in which the questionnaire/interview was answered. Their strengths and weaknesses are summarized in Table 1. Complementing both methods ensures a comprehensive understanding of individuals' exposure.

Table 1: Strength and weaknesses of both methods compared to one another

Research item	Smartphone survey and wearables (Method 1)	Go-/Ride-Along and wearables (Method 2)
Mixed-methods approach	Equal status concurrent: QUANTITATIVE + QUANTITATIVE	• Dominant status concurrent: QUALITATIVE + quantitative
Subjective perception of air and noise pollution	• Evaluation (very low – very high) possible • Statistical comparability ensured (correlations, regressions, significance tests) • No investigation about reasons/contexts for statistical correlations	• No evaluation (very low – very high) possible • No statistical comparability with measured data • In-depth (qualitative) insights into how environment is experienced/perceived, incl. situational context
Behavior en-route (protective actions)	• Route-choices and length of route can be investigated through GPS-tracking • No other actions/ behavior can be revealed	• Individual protective actions (e.g. reducing distance to emitter) or mobility behaviour can be discussed in-situ
Route-choices	• Routes taken can be detected • GPS-tracking for a longer period of time: different route-choices of greater sample can be detected	• Habitual, unconscious route choices can be detected (not mentioned post-hoc) • Reasons behind route choices can be revealed • Time and resource consuming: Not many GPS-trackings per participant can be provided
Validity of data	• Statistical validity, no qualitative investigations	• Only qualitatively, no statistical validity
Comparability of data	• Statistical comparisons possible	• Not possible, only qualitatively

5.2 Extending the personal exposure dimension: added value

With regard to the literature (chapter 2) and the strengths and weaknesses of the two mobile methods (chapter 4.1), we will now elaborate how the approaches can mutually support each other and present the extended personal exposure dimensions.

From the sensor data and smartphone-based surveys we revealed statistically proven differences in perceived and measured noise exposure (Ueberham et al., 2019). This is in line with previous studies on differences in measured and perceived noise, as discussed in chapter 2.2 (e.g. Kou et al. 2020). The questions arise, why a person perceives sometimes loud areas as pleasant and quiet areas as unpleasant.

The Go-/Ride-Along provides answers, showing that e.g. musicians, which may be recorded with high noise levels, positively influence the momentary experience (chapter 4). Not all loud sounds can be called "noise" – the source of the sound is influencing whether it is perceived as positive or negative. Sounds other than traffic noise, e.g. birds chirping, people talking or musicians, can improve the level of satisfaction of a route (Jensen, 2007). In unaccompanied mobile surveys (e.g. smartphone-based questionnaires) the frequencies of the noise level could help reveal what kind of noise is measured. Moreover, positive evaluations due to the situational context (e.g. olfactory or visual cues, knowledge, memories, life situation) can also result in differences in measured and perceived noise (chapter 4). As previous studies applying travel diaries and geographical ecological momentary assessments (GEMA) showed, the effects of context on perceived noise and psychological stress are important: e.g. even though measured noise at outside recreational activities or activities with friends are measured high, participants do not consider noise as a problem and had even a significantly lower level of momentary psychological stress (Kou et al. 2020). Wearable sensors completed by travel diaries or smartphone-surveys can give valuable insights into the places people visited, their momentary social contacts and the activities they performed. With these methods the situational context of people's exposure can be examined to some extent (Kou et al. 2020; Zhang et al. 2020). By accompanying the interviewees, however, the situational context is investigated more in-depth. The interviewer and interviewee can openly discuss the interviewees' experiences, practices and perceptions on-site and on-the-move. Summarizing, we argue that it is beneficial to use both, mobile smartphone-based surveys for statistical evidence (e.g. route evaluations or GEMA approaches) and qualitative methods, such as mobile interviews or travel diaries, for understanding the situational context behind them.

As for air pollution, the mobile interview provides information on the situational context in which air pollution is perceived and measured. As shown in the case study (chapter 4), route sections close to home are perceived as relieving ("*escaped*"), even though particles measured are high. Nature and leaving work are perceived as pleasant, in line with measured lower PNC. The external situation in the very moment or the past/upcoming activities are of importance for exposure perception. Measured high exposure is not always of concern for the interviewee, who is already feeling a relief of tension by nearly reaching their destination (chapter 4). Past/upcoming activities (being close to home or upcoming activities), knowledge of the route (e.g. worse part coming ahead), the external environment (e.g. nature) or life situations (e.g. past experiences, memories, vulnerability) impact air pollution exposure perception and evaluation in-situ.

On the one hand, transport and exposure research is increasingly applying mobile mixed-methods approaches (chapter 2). Looking at transport planning or environmental policy, on the other hand, we still see a strong focus on objectively measured data and statistically defined thresholds (Verbeek 2018). Of course, this is important to make sound decisions for healthy transport planning, yet, it neglects the importance of perceptions, experiences and situational contexts and its potential to improve commuters' wellbeing. As for the question what to consider when talking about "personal exposure" – the objectively measured exposure, the subjectively perceived or a combination of both – we argue, that a combination of both is representing the exposure situation comprehensively. Considering objectively measured and subjectively perceived exposure is crucial, yet, other contextual factors, such as e.g. vulnerability, socio-economic data and the discussed situational context in-situ, are important for promoting health and wellbeing (Bartels et a. 2015; Kou et al. 2020; Verbeek, 2018). Additionally, accompanying the person, similar to travel diaries (chapter 2), even opens up another exposure dimension: the situational context of personal exposure. All dimensions are linked and influence one another (Fig. 6). This is important for research, but should also gain more importance in planning decisions.

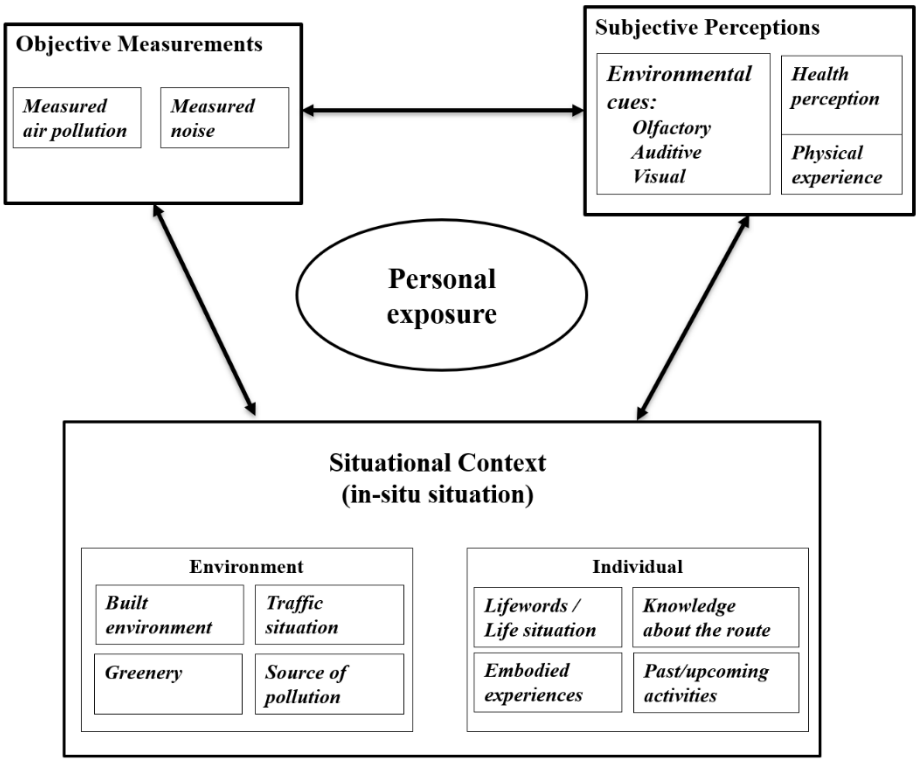

Figure 5: Extended dimension of personal exposure in traffic: Interlinkages of objective measurements, subjective perceptions and situational context.

5. Conclusion

We have discussed the extended dimensions of personal exposure, which consider the situational context of exposure on-the-move. We presented a novel mixed-methods approach using Go-/Ride-Alongs and wearable sensors, contrasting it to a reference method. Both methods acknowledge the interviewees as experts of their own environment and document how a person perceives, experiences and behaves during daily commute (Carpiano, 2009; Evans & Jones, 2011; Kusenbach, 2003). Based on mobile ethnographic research and movement as derived from the "new mobilities paradigm", we argue that it is important to consider urban dwellers as experts of their own personal exposure (Latour, 2005; Sheller & Urry, 2006). Further research should give attention to mobile methods – both qualitative and quantitative – and their benefits when mutually supporting each other.

We argue that the methodological approaches in personal exposure research should further comprise mixed-methods and qualitative mobile methods. With regard to planning for healthy cities, stronger engagement in participatory approaches could be a solution to capture not only the measured exposure, but also incorporate how people perceive air pollution and noise. This is of importance, considering that decisions in transport planning and policy are usually based on objectively measured data and decision-makers' views on what commuter need are not always in line with the actual reported needs (Marquart et al., 2020; Verbeek 2018). Wearable sensor data combined with quantitative mobile methods, which give statistical evidences, or with qualitative mobile methods, which give in-depths contextual insights, are beneficial. Therefore, the exposure dimensions can be extended towards the situational context in which the exposure takes place, without neglecting the actual measured exposure nor the subjectively perceived. As for urban planning, the built environment, traffic situation, greenery and source for pollution as well as people's situational context influence how people perceive air pollution and noise. This is of importance, because "context affects health" (Kestens et al., 2017) and people's health and wellbeing differs in time and space (Sharp et al., 2015). Approaches from health research investigate *how* and *where* people are exposed to environmental stressors, drawing on quantitatively measured subjective wellbeing and measured exposure. Methods like the presented give evidence on *what* and *why* people actually perceive and experience during commute. Approaches like "people as sensors" draw conclusions of people's wellbeing from quantitatively measured data (Kabisch et al., 2021; Kestens et al., 2017; Sharp et al., 2015; Zeile et al., 2016). Our qualitative mobile approach specifically documents people's stated experiences and behavior in-situ and on-the-move.

In view of the adverse health and wellbeing impacts of air and noise pollution, it is important to consider urban dwellers' experiences and perceptions about their daily commute. This encourages community engagement, the feeling of self-efficacy and strengthens community ownership; it encourages people to pay more attention to the spaces they pass – thus, it is about stressing "*their* own opinions about *their* environment" (Hein et al., 2008). Additionally, knowing how the public experiences their city is important for practitioners (Evans & Jones, 2011). Considering the limited literature on perceived and measured exposure on-the-move and the possibilities of mobile methods as presented, methods like these, when applied by transport research and planning, have the opportunity to enhance communities' environmental health literacy, increase urban dwellers self-efficacy and support successful planning decisions adapted to people's needs.

Acknowledgement

This paper highly benefitted from the valuable comments and helpful suggestions from Kerstin Stark which helped to finalize the article..

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Appendix 1: Sample characteristics

Participant #	Mode of transport	Occupation	Age	Gender	Average noise (dB(A))*	Average PNC per dm³*
RA1	Bicycle (Ride-Along)	Employed	55	f	66,3	3713
RA2	Bicycle (Ride-Along)	Employed	30	m	68,5	11639
RA3	Bicycle (Ride-Along)	Paternity leave	-	f	63,3	2240
GA4	Walking+subway+bus (Go-Along)	Employed	59	f	65,2	13118
RA5	Bicycle (Ride-Along)	Employed	42	f	71,6	15967

GA6	Walking+subway (Go-Along)	Student	32	f	62,7**	18389
RA7	Bicycle (Ride-Along)	Employed	31	f	68,3**	9454
GA8	Walking+subway (Go-Along)	Student	25	m	63,1**	15197
RA9	Bicycle (Ride-Along)	Student	24	m	73,1	25492
RA10	Bicycle (Ride-Along)	Employed	42	f	72,8	2965

* Interviews/Measurements were taken on different days and different time of the days, on the routes chosen by the interviewee. This results in the differences in particles and noise levels. PNC was converted from ft^3 into dm^3.
**Some values are missing and were not used for analysis; average noise level not representative for entire route of this interviewee.

Appendix 2: Semi-structured mobile interview questionnaire (translated from German)

A. Mobility behavior
    - Why do we take this route?
    - Did you take another route in the past? Why?
    - We have turned to the …/changed the side of the road/…, why did we not take this route/side of the road/…?
B. Mode of transport
    - How do you perceive the mode of transport at the moment?
    - Have you used/do you use another mode of transport sometimes? Why?
C. Environmental perception
    - How are you feeling regarding your environment at the moment? Do you like it? Dislike it? Why?
    - How do you perceive your environment at the moment? Concentrate on what you hear, smell, see?
    - You said before, you perceived the environment as [*stressful, beautiful, pleasant*, …], how do you feel right now?
D. Health and Wellbeing
    - You said, you perceived the environment as [*stressful, beautiful, pleasant*, …]. Does it have an impact on you physically and your wellbeing? You have talked about how you [*don't*] like [*the noise/air/...*], how would you translate [*don't*] like, what does it do to you physically or mentally?
    - How do you feel regarding your health at the moment?
    - Do you have strategies, to reduce or avoid stressors such as air pollution and noise *[questions asked when people undertake protective actions]*
E. Optional: Authority Arguments for further stimulating a narrative *[later during the mobile interview, after interviewee talked about air pollution and noise him-/herself]*
    - In Germany, air pollution and noise exposure are discussed in media and politics. Have you considered the impacts on your health in terms of air pollution / noise pollution?
    - Have known, that noise over 55 dBA for a longer period of time is already impacting your health according to the WHO? Usually streets with a high traffic volume exceed even 70 dB(A).
    - Have you known that, according to the WHO, the burden of disease from urban air pollution is placed at top 1 environmental health risk in urban areas. Followed by noise.

- We have now [*referring to the display of the particle number counter*] particles, that is translated in [*bad/good*] air quality, compared to [*street XY*] before.

F. *Ad-hoc questions*