Healthy and pleasant commuting in cities

Exploring cyclists' and pedestrians' personal exposure, wellbeing and protective practices on-the-move

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von

Heike Marquart, M.A.

Präsidentin der Humboldt-Universität zu Berlin:
Prof. Dr. Julia von Blumenthal

Dekanin der Mathematisch-Naturwissenschaftlichen Fakultät:
Prof. Dr. Caren Tischendorf

1. Gutachterin: Prof. Dr. Barbara Lenz
2. Gutachter: Prof. Dr. Uwe Schlink
3. Gutachterin: Prof. Dr. Tobia Lakes

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Abstract

Conventional cars with combustion engines are responsible for greenhouse gas emissions affecting the climate, health impacting air pollutants and traffic related noise whilst taking up public space. To reduce conventional private cars in cities, the promotion of cycling and walking is a promising alternative. Cycling and walking is not only space-saving, pollution-free and noise-abating, it also supports people's physical activity and wellbeing. It is societally beneficial to make cycling and walking more attractive by making it a pleasant and healthy experience. Improving the trip and reducing health burdens whilst in traffic can contribute to that. One of these health burdens is the exposure to environmental stressors: air pollutants, such as particulate matter, and high noise levels. This thesis investigates these health burdens and other factors influencing cyclists' and pedestrians' wellbeing and practices en route. Moreover, as a growing usage of smartphones has occurred in recent years, the possibilities of mobility apps for supporting a healthy and pleasant trip are investigated. Hence, the scope of this thesis is to combine the topic health, specifically air pollution and noise, wellbeing and pleasant mobility with possibilities of mobility apps. First, the thesis explores how cyclists and pedestrians perceive their personal exposure towards air pollution and noise. Additionally, other factors influencing commuting experience, perceived health and wellbeing on-the-move are examined. This is contrasted to actual measured particulate matter and noise. A mixed-method design is applied: qualitative interviews on-the-move with 28 cyclists and pedestrians in Berlin, Germany, so called go-/ride-alongs, are complemented by wearable sensors measuring particulate matter and noise. The perceived and measured exposure is visualized and analysed via Geographic Information Systems (qualitative GIS). The results show spatial discrepancies and coherences between perceived and measured air pollution and noise and other factors influencing wellbeing on-the-move. The go-/ride-alongs highlight that the situational context, sensory awareness (e.g. greenery/water, urban aesthetics, interesting sites) and social cues (e.g. seeing other people, neighbourhood areas) are important for a perceived healthy and pleasant commute, even in polluted areas. However, perceived noise and polluted air, not always in line with the measurements, also influence wellbeing on-the-move. Cyclists and pedestrians frequently use hidden-paths, cover their mouth/nose or apply emotions focused coping to protect themselves. Second, this thesis identifies how far health impacting factors are considered in research using mobility apps in order to identify their possibilities for supporting a healthy commute. A literature review reveals that current research applying mobility apps is lacking the consideration of health topics, such as air pollution and noise. It is proposed to integrate health topics in mobility app development. Following these findings, the thesis ultimately investigates communication options to inform cyclists and pedestrians about healthy and pleasant commute. Focus groups were applied, exploring experiences with air pollution and noise and information needs. It is shown that pollution should be made relatable, feasible coping strategies should be presented and self-efficacy should be increased. Pleasant trip characteristics could be included in a healthy mobility app. It is a matter of not only focusing on health impacting exposure, but also factors that improve wellbeing on-the-move. The findings are of interest for mobility app development, but also encourage new directions for urban and transport planning and policy. If active mode users' experiences, perceptions and practices are considered, the attractiveness of cycling and walking can be enhanced, encouraging more people to cycle or walk. Hence, active modes can unfold their potential for supporting the transformation towards liveable, healthy and environmentally friendly cities in the future.

Zusammenfassung

In dieser Doktorarbeit wurde untersucht, welche Faktoren Wohlbefinden, wahrgenommene Gesundheit und Mobilitätspraktiken von Radfahrenden und Fußgänger:innen während des Unterwegsseins beeinflussen. Ziel war es, die persönliche Exposition gegenüber gesundheitsbelastenden Stressoren wie Feinstaub und Lärm unterwegs zu messen und diese der individuell wahrgenommenen Belastung gegenüberzustellen. Zudem wurden weitere Faktoren, die das Wohlbefinden während des Unterwegsseins beeinflussen, untersucht. Die Arbeit beleuchtet überdies, wie Fahrradfahrende und Fußgänger:innen über gesunde und angenehme Mobilität in der Stadt informiert werden können. Hierbei liegt ein Fokus auf Mobilitäts-Apps und der Frage, inwiefern das Thema Gesundheit, speziell Luftschadstoff- und Lärmbelastung, sowie angenehme Routenumgebungen in Mobilitäts-Apps integriert werden. Mit 28 Radfahrenden und Fußgänger:innen in Berlin, Deutschland, wurden mobile qualitative Interviews (so genannte Go- bzw. Ride-Alongs) durchgeführt und mit tragbaren Sensoren zur Messung von Feinstaub und Lärm ergänzt. Die geo-lokalisierten Feinstaub- und Lärmmessungen konnten so mit den qualitativen Daten und dem situativen Kontext, in dem die Daten erhoben wurden, zusammengeführt, visualisiert und analysiert werden und Unterschiede und Übereinstimmung zwischen wahrgenommener und gemessener Belastung sowie weitere, das Wohlbefinden beeinflussende Faktoren, untersucht und in ihrem situativen Kontext betrachtet werden. Der situative Kontext (z.B. das Verlassen der Arbeit, das Erreichen des eigenen Wohnviertels), die sensorische Wahrnehmung (z.B. Grünflächen/Wasser, Ästhetik städtischer Strukturen, Straßenmusiker:innen) und soziale Aspekte (z.B. Menschen bei Freizeitaktivitäten, die Nachbarschaft) beeinflussen, ob das Unterwegsseins in der Stadt als gesund und angenehm empfunden wird. Diese Faktoren können in vergleichsweise gemessenen hoch belasteten Situationen ausgleichend wirken. Auch Schleichwege, um Belastungsorte zu umfahren, und Schutzmaßnahmen, wie das Zuhalten von Mund/Nase, zeigten sich als Schutzpraktiken auf Alltagswegen. Aber auch als belastend wahrgenommener Lärm und Luftschadstoffe, die nicht immer mit den Messungen übereinstimmen, können das Wohlbefinden beim Unterwegssein negativ beeinflussen. Um zu untersuchen, wie Feinstaub- und Lärmbelastung auf Alltagswegen kommuniziert werden kann, wurden Informationsmöglichkeiten für eine gesunde und angenehme Mobilität exploriert. In einem Literaturreview wurde aufgezeigt, dass Gesundheitsthemen, insbesondere Luftschadstoffe und Lärm, kaum in Forschung zu Mobilitäts-Apps berücksichtigt werden. In den daran anschließenden Fokusgruppen mit Teilnehmer:innen aus den Go- bzw. Ride-Alongs wurde ermittelt, wie gesunde und angenehme Routen kommuniziert werden sollten. In den Fokusgruppen erhielten die 20 Teilnehmer:innen Feedback zu ihrer gemessen Belastung, diskutierten ihre wahrgenommene Gesundheit, Schutzmechanismen, ihre Routenwahl und ihr Informationsbedürfnis. Ein zentrales Ergebnis war die Relevanz von verständlichen Informationen und umsetzbaren Routenalternativen. Es wurde eine ‚pleasant routing app' vorgeschlagen, die angenehme und gesunde Routenaspekte integriert und auf partizipative Mapping-Methoden zurückgreift. Abschließend zeigt diese Doktorarbeit Möglichkeiten auf, eine als gesund und angenehm wahrgenommene Mobilität in der Stadt zusammen mit messbaren Umweltstressoren in den Blick der Planung zu rücken und diese verstärkt bei der Entwicklung von Mobilitäts-Apps zu berücksichtigen. Um die Attraktivität des Fahrradfahrens und zu Fuß Gehens zu steigern, sollten die Erfahrungen, Wahrnehmungen und Praktiken von Radfahrenden und Fußgänger:innen im Fokus stehen, sodass aktive Mobilität ihr Potenzial entfalten kann, zu einer lebenswerten, gesunden und umweltfreundlichen Stadt beizutragen.

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Abbreviations

AR – Augmented Reality

dB(A) – A-weighted decibels

EEA – European Environmental Agency

EHL – Environmental Health Literacy

GHG – Greenhous gas emissions

GIS – Geographic Information System

ICT – Information and Communication Technology

OSM – Openstreet Map

PADM – Protective Action Decision Model

PM – Particulate Matter

PMT – Protection Motivation Theory

PNC – Particulate Number Count

VGI – Volunteered Geographic Information

VR – Virtual Reality

WHO – World Health Organization

1. Introduction

Everyday people move around the city for daily purposes such as going to work. Some commute by car, others by bicycle, on foot or public transport. When moving around in cities, people are directly exposed to the passing environment. The urban environment and related environmental stressors, such as air pollution or noise, affect human health and wellbeing (Krzyzanowski et al., 2005; WHO, 2011). Specifically, cyclists and pedestrians, also on their way to public transport, are exposed to environmental stressors, but also experience positive environmental influences on-the-move. Cycling and walking is an embodied experience, it is shaped by the bodily movement itself and influenced by the sensually perceived route environment on-the-move (Cresswell, 2010; Degen & Rose, 2012; van Duppen & Spierings, 2013). Meanwhile, mode and route choices can be influenced and supported by information and communication technologies, especially smartphones (Dal Fiore et al., 2014; Lenz, 2011). Smartphone apps with a focus on mobility, so called mobility apps, are increasingly used to organize mobility in cities (Andersson et al., 2018; Gössling, 2017). This thesis sheds light on possibilities for supporting healthy and pleasant mobility. It is the aim to understand what factors influence a perceived healthy and pleasant trip for cyclists and pedestrians and detect to what extend the exposure to air pollution and noise influences perceived health and wellbeing. Consequently, possibilities of mobility apps to improve healthy and pleasant commuting in cities are explored.

1.1 Background and motivation: healthy and pleasant cycling and walking

Urban areas are hotspots of adverse lifestyles as well as environmental exposure, impacting human health in a variety of ways (Khreis et al., 2017). Specifically, people's sedentary lifestyle, air pollution, noise, high temperatures, urban heat island and lack of green spaces impact human health in cities (Khreis et al., 2017; Nieuwenhuijsen & Khreis, 2019). Tackling these health risks following international recommendations could lower mortality[1], with physical activity having the greatest potential for preventing deaths, followed by reducing air pollution exposure, traffic noise and heat (Mueller et al., 2017). Moreover, climate change will explicitly affect urban areas now and in the future, around the world as well as in Europe (EEA, 2016b). Increasing temperatures and heat waves compromising the burden of air pollution will affect cities and be as well a health risk for urban dwellers[2] (EEA, 2016b). Therefore, it is both a global and local societal goal to mitigate climate change and lower its impact on cities, as it is to improve human health in urban areas to make cities a sufficient place to live.

Urban transport is closely linked to topics such as climate change, environment and health and can be regarded as both: detrimental, but also poses benefits for creating healthy and sustainable

[1] A study from Barcelona, Spain, showed that nearly 20% of mortality annually could be preventable if international recommendations regarding physical activity, air pollution, noise or heat would be followed (Mueller et al., 2017).

[2] In the thesis, urban dwellers or residents refer to people living and moving around in the city.

cities (Nieuwenhuijsen & Khreis, 2019). Motorized road traffic with combustion engines is a major emitter of climate impacting greenhouse gas (GHG) emissions and responsible for a quarter of GHG emissions in the European Union, emits health impacting air pollutants and is the leading source of environmental noise (EEA, 2016a, 2020b; Sims et al., 2014). Being exposed to adverse traffic-related air pollution is associated with a variety of physical and mental health impacts (EEA, 2020a; Krzyzanowski et al., 2005). Specifically, PM2.5, referring to particulate matter with a diameter smaller than 2.5µm, is regarded as the leading environmental health risk factor in European cities causing a high number of premature deaths a year[3] (EEA, 2020a; Hänninen et al., 2014). Also, the exposure to traffic-related noise impacts physical and mental health, for example due to annoyance (WHO, 2011, 2018). Annoyance from road traffic noise is constituting most of the burden of environmental noise in western Europe, next to sleep disturbance (WHO, 2011). Noise is among the leading environment health risk factors in Europe, following particulate matter (Hänninen et al., 2014). It is estimated that at least 1 million healthy life years are lost each year in western Europe due to traffic-related noise (WHO, 2011). Promoting walking and cycling for everyday trips, which are noise-abating and pollution free, can be a possible way to address these health impacts and lower GHG emissions.

In Germany, one third of all trips are work and education related (in this thesis considered as commuting trips) (Vollmer & Gruschwitz, 2019). By supporting the usage of active modes of transport not only climate change, but also negative health effects can be tackled: Commuting by bicycle or on foot promotes physical activity and fitness, prevents illness and improves the overall quality of life and wellbeing (Mouratidis et al., 2019; Mytton et al., 2016; Synek & Koenigstorfer, 2019). Walking and cycling has gained attention in recent years. One third of all trips in Germany are made by bicycle or on foot, with an increase in cycling since 2002 (Vollmer & Gruschwitz, 2019). Public transport users can also be considered as active mode users, since they spent a substantial amount of time walking (Hillnhütter, 2016). Promoting cycling, walking and public transport is essential for a transition towards sustainable, i.e. environmentally friendly, healthy and socially just, mobility in urban areas (German Environment Agency, 2020). In recent years priorities on promoting sustainable mobility have been placed on the policy agenda, for example the European Urban Mobility Framework (European Commission, 2021) or the German national cycling strategy (Federal Ministry for Digital and Transport, 2022). Generally, cities should be designed "of such quality and at a suitable scale that people would not need to have a car" (Banister 2008, p. 74). Quality in that sense can refer to cycling infrastructure or safety issues, but also to a perceived pleasant environment, which is important when cycling and walking through urban space: the visual, olfactory and auditive experiences en route (Degen & Rose, 2012; van Duppen & Spierings,

[3] The European Environmental Agency (EEA) provides numbers of premature deaths caused by PM2.5 in Europe per year for each country, showing that all in all approximately 417.000 premature deaths a year in Europe are attributable to PM2.5 (for more information see: the "Air quality in Europe" Report (EEA, 2020a)).

2013). As van Duppen and Spierings (2013) point out, “commuting cycling is an everyday practice in which experience is mediated through the senses” (van Duppen & Spierings, 2013, p. 235). This thesis draws attention to the question how to increase the usage of active modes, by specifically investigating cyclists’ and pedestrians’ sensory experiences on-the-move and how they perceive their passing environment.

However, cyclists and pedestrians are directly exposed to the aforementioned air pollutants and noise. This thesis focuses on two leading environmental health risks in urban areas when addressing health: particulate matter (PM2.5) and noise. Specifically, cyclists’ and pedestrians’ exposure of traffic-related particulate matter and noise. Particulate matter und noise are high alongside road and rail traffic (Apparicio et al., 2016; Chaney et al., 2017). For example, cyclists have high noise exposure exceeding 60 dB(A) en route in European cities (Okokon et al., 2017), whereas according to the WHO guidelines, road traffic noise shall not exceed 53 decibels L_{den}[4] on average (WHO, 2018). Cyclists and pedestrians recorded higher measurable particulate matter exposure than other transport users (Chaney et al., 2017; Okokon et al., 2017). Minimizing negative impacts on wellbeing, for example by lowering air pollution or noise exposure, is argued as a promising way forward for transport policy, could encourage cycling and walking and improve its health and wellbeing effects (Reardon & Abdallah, 2013). Moreover, not only the measurable exposure impacts health and wellbeing, also the perceived exposure has an effect (Orru et al., 2018). Perceived and measured exposure are not always in line (Ueberham et al., 2019), hence, it is important to consider both. Consequently, this thesis explores how to make commuting by bicycle or on foot (incl. public transport) more attractive by addressing measurable and perceived exposure to air pollution and noise en route.

For increasing the attractiveness of active modes, informing about healthy and pleasant trips is considered relevant. Informing about mobility options is nowadays increasingly relying on information and communication technologies (ICT), which influence people’s travel choices and desire to travel (Dal Fiore et al., 2014; Gössling, 2017; Lenz, 2011). With location-aware mobile devices information can be gathered, one’s own location be checked in real time and one can be “socially networked” whilst on-the-move (Sheller, 2018). The usage of location-aware smartphones influences mobility practices, offers people new reasons to be mobile and helps them to make informed mobility choices (Dal Fiore et al., 2014; Lenz, 2011). Receiving travel information via smartphone apps enables to choose a route or transport mode based on certain information, for example effectivity and convenience (e.g. time, distance, sharing, payment options), health (e.g. physical activity) or eco-friendliness (e.g. less CO2-emissions) (Andersson et al., 2018; Gössling, 2017). Informing about health risks related to a certain mode or route has the potential to increase recognition and understanding of the severity and

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[4] L_{den} (day-evening-night noise level (as an opposite to L_{night} referring to the night noise level), “refers to an A-weighted average sound pressure level over all days, evenings and nights in a year, with an evening weighting of 5 dB and a night weighting of 10 dB” (EEA, 2020b). The A-weighted average (called dB(A)) means that the frequency is filtered that it represents the loudness of a sound as perceived by the human ear.

vulnerability to a risk. Combined with increasing people's self-efficacy and response efficacy to cope with the risk, it can ultimately motivate and support people to undertake health protective practices and tackle the risk on a community-level (Finn & O'Fallon, 2017; Gray, 2018; Lindell & Perry, 2012; Maddux & Rogers, 1983). Informing about the health risk of air pollution or noise en route and providing options to avoid exposure is considered to improve health and wellbeing of cyclists and pedestrians. Mobility apps which organize daily travel could address air pollution and noise related health-concerns of cyclists and pedestrians and thus, overall improve healthy active commuting in cities. Therefore, the question arises what possibilities this technology offers to inform about mobility choices which protect health, support a pleasant trip and are beneficial for society.

1.2 Research aim and questions

This thesis aims at investigating possibilities for supporting healthy and pleasant mobility[5]. It considers cyclists' and pedestrians' subjective sensory experiences and how they influence wellbeing on-the-move (see section 2). Wellbeing is considered part of the broader term health and is defined based on the ecological perspective of wellbeing. It focuses on how human-environment interactions impact wellbeing, acknowledging that place and space are decisive for wellbeing (Nordbakke & Schwanen, 2013). Wellbeing during travel is influenced by the experience made during the trip and the movement itself, or as Nordbakke and Schwanen (2013) argue, "the movement is itself a place emerging out of human-environment interactions and affects one's happiness, freedom, safety and capability" (Nordbakke & Schwanen 2013, p. 15). As for physical health, this thesis examines air pollution, focusing on particulate matter, and noise as part of the interrelationship of transport, the environment and health (Nieuwenhuijsen & Khreis, 2019). Both are two of the leading environmental health risk factors in European cities (Hänninen et al., 2014). In this thesis, air pollution refers to measurable particulate matter (PM2.5), and the overall perception of air pollution. Noise, as defined by the World Health Organization (WHO), refers to environmental noise emitted by all sources (except workplace), whereas the European Environmental Agency (EEA) refers to noise as "unwanted or harmful outdoor sound created by human activity, such as noise emitted by different means of transport […] and industrial activity" (EEA 2020b, p.8). This thesis relates to the definition by the WHO, because both the measured and reported perceived noise were examined and the noise source could not necessarily be distinguished.

The scope of this thesis is to combine health, specifically air pollution and noise, wellbeing and pleasant mobility with possibilities of mobility apps. The goal is to understand how cyclists and

[5] This thesis refers to the term *mobility*, coming from a rather social sciences perspective, compared to the rather technical-organizational perspective of the term *transport*, acknowledging the needs and abilities of people regarding their movement, activities and accessibility rather than distances and trips, individual view (compared to the aggregate view of transport) and taking the psychological, cultural and social aspects of movement into consideration (Wilde & Klinger, 2017). In-depths presented in section 2.1.

pedestrians perceive and are exposed to air pollution and noise and what other factors influence a perceived healthy and pleasant commute in the city. Additionally, possibilities of mobility apps for supporting a pleasant and healthy commute are examined, including the provision of air pollution and noise exposure information but also considering other decisive factors for a pleasant commute.

In a first step, the current state of empirical research applying mobility apps is examined. It is investigated to what extend the mobility apps applied in current empirical research consider mobility-related health components. The related research questions are as follows:

Q1. To what extent and how is the 'health dimension' (specifically air pollution and noise) considered in mobility apps applied in mobility behaviour change research?

Q1a. Which informational dimensions do the applied mobility apps comprise and what effects on mobility choices do they have?
Q1b. To what extent are air pollution and noise or other health-promoting components considered and how can they further be integrated?

The aim is to systematically review information, which is presented to the participants in the empirical studies by mobility apps. Furthermore, the reported effects of the mobility apps on mobility choices are explored. Mobility-related health components included in the apps are identified, with a focus on air pollution and noise information. Based on the reviewed empirical studies, a theory-based inclusion of health components in mobility apps is proposed.

In a second step, cyclist's and pedestrian's measured and perceived exposure and factors impacting their health and wellbeing are considered. It is explored how they themselves experience their trip, how they perceive their exposure, health and wellbeing en route and if they feel at risk of air pollution and noise. Knowing people's experienced commute and perceived exposure is regarded as relevant to successfully communicate and inform about measurable air pollution and noise. Hence, the second research question is as follows:

Q2. How is exposure to air pollution and noise perceived while moving in the city and how does that impact practices en-route?

Q2a. How to examine perceived and measured exposure and related practices on-the-move?
Q2b. Are perceived and measured air pollution and noise in line and if not, what other factors are decisive for a perceived healthy or pleasant commute?

These research questions draw attention to inconsistencies and similarities in measured and perceived exposure. The aim is to investigate the objectively measured and the subjectively perceived exposure together. Reasons behind differences and similarities in perceived and measured exposure are investigated. Relevant factors, which impact a perceived healthy and pleasant commute during high exposure levels, are examined.

Drawing on the findings from the first two research questions, the third research question draws attention to exposure information. Urban commuting routes are often inevitable compared to mobility as a leisure activity, hence, supporting healthy everyday commuting routes is regarded as essential. The third question of this thesis is therefore:

Q3. How to inform about a healthy – low air pollution and noise exposure – and pleasant commute on daily (inevitable) routes in the city?

Q3a. How should information on health impacting factors en route, such as air pollution and noise, be designed to support healthy and pleasant mobility in urban areas?
Q3b. Is information provision about exposure on daily (inevitable) routes a worthwhile strategy to support healthy and pleasant mobility?

The aim is to identify the influence of exposure information on the perception, (intended) route and mobility choices of cyclists and pedestrians. It is investigated how to design exposure information and it is examined in how far informing about exposure is worthwhile. Ultimately, possibilities of information provision for supporting a healthy and pleasant commute are discussed together with cyclists and pedestrians.

1.3 Structure of the thesis

The cumulative thesis comprises four connected research articles (Fig. 1). Each of the articles answers one of the main research questions and altogether they address aspects of healthy and pleasant commuting, including exposure and wellbeing on-the-move. Research question Q2 is divided into two articles due to the methodological and content scope. In the course of this thesis, two supplementary and related research articles were published: a conference proceeding and a literature review. Their abstracts can be found in the Appendix A for interested readers.

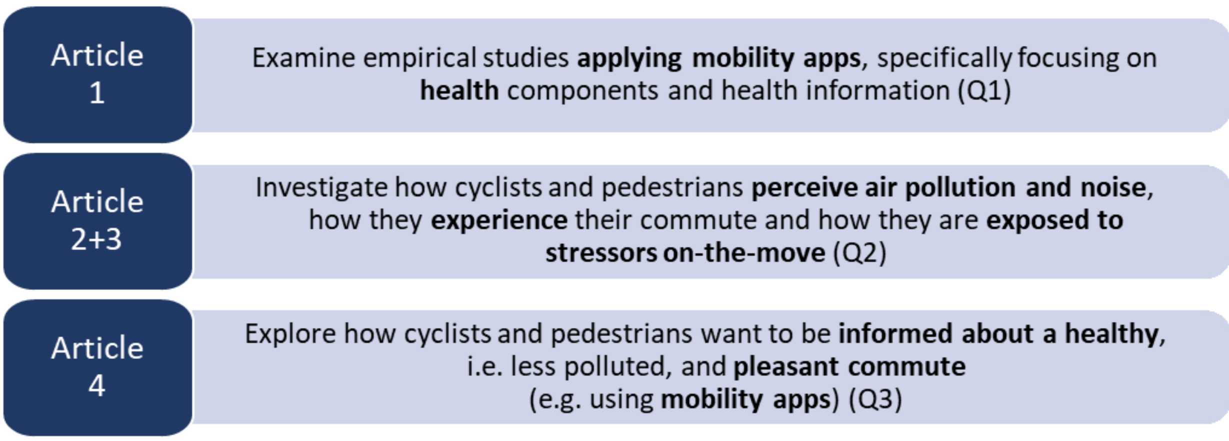

Figure 1: Articles of the cumulative dissertation and related research aims

Following the introduction (section 1), a comprehensive overview of the theoretical background is provided (section 2). Section 2 presents how the thesis is embedded in the field of geography and mobility research and draws connections to risk communication and health theories and concepts. In section 3 the study design is presented and the methods used are described. The methods will also be described in the respective articles. Section 4 is the core of the thesis and comprises four research articles. The section contains a short introduction to the articles and contextual transitions between the articles to guide the reader. Table 1 presents the articles of this thesis, their scope and topics. Finally, section 5 brings together the findings from the research articles, draws conclusions and presents this thesis' contribution to scientific research, policy and planning and concludes the thesis with an outlook.

Table 1: Overview of the published articles as part of the cumulative thesis (see section 4)

Article	Title	Authors	Journal	Scope and topic	Section
I	Promoting sustainable mobility: To what extent is "health" considered by mobility app studies? A review and a conceptual framework	Marquart, H., Schuppan, J.	Sustainability	**Literature review findings** Mobility apps and health	4.1
II	Extending the dimensions of personal exposure assessment: A methodological discussion on perceived and measured noise and air pollution in traffic	Marquart, H., Ueberham, M., Schlink, U.	Journal of Transport Geography	**Methodological and empirical findings** Go-/ride-alongs and wearable sensors	4.2
III	How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute	Marquart, H., Stark, K., Jarass, J.	Journal of Transport & Health	**Empirical findings** Go-/ride-alongs and wearable sensors	4.3
IV	Informing about the invisible – Communicating en route air pollution and noise exposure to cyclists and pedestrians using focus groups	Marquart, H.	European Transport Research Review (submitted)	**Empirical findings** Focus groups on risk communication and pleasant routing	4.4

2. Theoretical background

For researching how air pollution and noise are perceived by cyclists and pedestrians on-the-move, how the experienced environment impacts their everyday mobility and for investigating how to communicate air pollution and noise to cyclists and pedestrians, different theoretical backgrounds have to be considered. Therefore, this thesis refers to theories, concepts and approaches from social geography, mobility research as well as health research.

Firstly, the "new mobilities paradigm" will be introduced, which draws attention to the importance of considering perceptions and **sensory awareness** on-the-move, as well as the **practice** of movement (section 2.1). Secondly, the term of environmental **perception** as defined in the disciplinary field of geography will be explained, drawing attention to the field of cognitive geography (section 2.2). Thirdly, the focus will shift to the field of health research, providing the theoretical background for researching **risk perception** (e.g. risk from air pollution and noise) and how to motivate people to protect themselves (section 2.3). Finally, the concept of Environmental Health Literacy (EHL) will be presented, which will be used to identify exposure **risk communication** and information needs concerning air pollution and noise on-the-move (section 2.4). All of these approaches offer a valuable background for this thesis (Fig. 2).

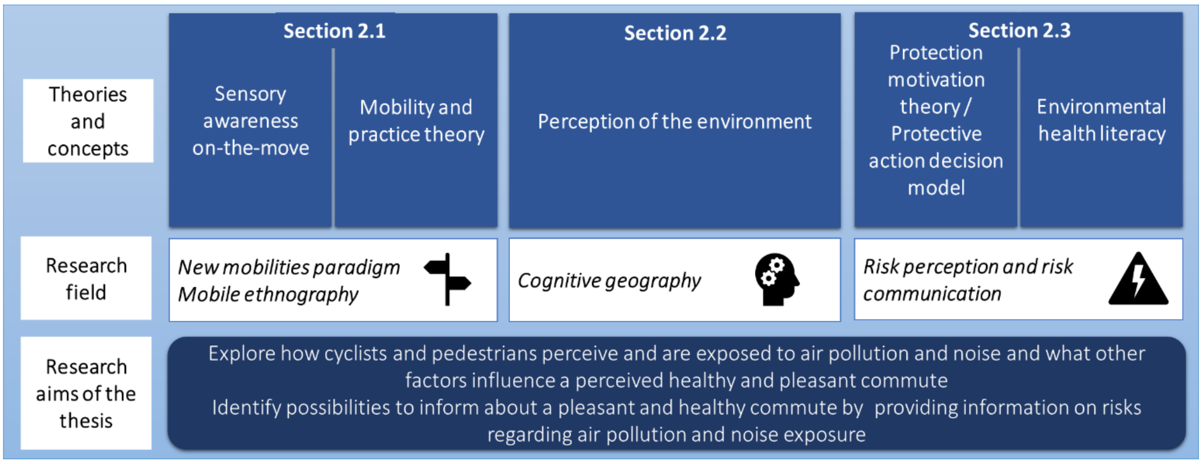

Figure 2: Theories, concepts and research fields this thesis addresses

2.1 Commuters on-the-move: new mobilities paradigm and mobility practices

Following the "new mobilities paradigm", which was introduced by Sheller and Urry (2006), a shift from traditional transport research towards the term mobility and a new understanding of being mobile took place. The term 'mobility' acknowledges the needs and abilities of people regarding their movement, the activities and accessibility of activities rather than distance and trips and considers mobility from an individual perspective, which considers the psychological, cultural and social aspect of movement (Wilde & Klinger, 2017). People move rarely because of the physical act of movement itself, rather is mobility the basis of participating in society (Hunecke, 2015). Traditional transport research has often argued from a quantitative logic, focusing on technical-organizational aspects of transport coming from engineering and economics without considering the subjective meanings of transport (Wilde et al., 2017). As a reaction to that technical-organizational view, work following the new mobilities paradigm argues that transport research has looked at movement too much as an "empty space that needed to be limited" (Cresswell, 2010, p. 18). The embodied experiences of movement, the context (e.g. social) in which the moving body operates or the activities occurring on-the-move need to be considered (Sheller & Urry, 2006). As a result, mobility research centers around the individual. Mobility is not only about covering a physical distance from a place A to a place B, but mobility is defined as a form of social practice, which contributes to personal wellbeing (Wilde et al., 2017). The studies which are rooted in the new mobilities paradigm range from researching the micro-movements of the individual body to questions of global travel, considering as well the mobility of goods, the digitized act of moving through virtual reality or the digitized world that enables people to move through space while connecting with the world "on-the-go" (Cresswell, 2010; Sheller & Urry, 2006). It is argued that movement and travel should not be considered as a given and the time of being in-transit should not be seen as a "dead time" which should be minimized, but rather take a holistic understanding of mobility and "take the actual fact of movement seriously" (Cresswell, 2010, p. 18). Mobility research focuses for example on the physical movement of the body or reaching a specific place, the representation of movement as, for example, freedom, or the embodied practice of movement as the individual experiences it (Cresswell, 2010). This thesis focuses on experiences, perceptions and practices of cyclists and pedestrians during movement (i.e. on-the-move) and specifically considers the time being in transit (Article II, III and IV), hence, it relates well to the work following the new mobilities paradigm.

When researching mobility and movement of individuals, practice theory is a valuable theoretical background. Research in geography and mobility has increasingly taken into consideration the term practice and its associated methodologies (see, for example, Everts et al., 2011; Greene & Rau, 2016; Manderscheid, 2019; Schäfer & Everts, 2019; Stephan, 2019; Wilde, 2013). Schatzki (2001), an important representative of practice theory, defines social practices as a "set of actions" that "are either bodily doings and sayings or action that these doings and sayings constitute" (Schatzki, 2001, p. 56). Hence, it is about *how* something is happening, not *what* is happening (Kühl, 2016; Schatzki, 2001). For researching both these "doings" and "sayings", engaging with a person in the field through a mobile or walking interview, i.e. interviewing on-the-move, is valuable (Kühl, 2016; Wenzl et al., 2019). Hence, for researching cyclists' and pedestrians' doings and sayings on-the-move, taking practice theory as a background for this thesis is beneficial (see section 3.3). Based on Shove et al. (2012) "practices involve the active integration of materials, meanings and forms of competence" (Shove et al., 2012, p. 45), which mutually shape one another. Taking the practice of cycling to work as an example, materials would be a bicycle or a route/destination to cycle to or cycling infrastructure, meanings could involve emotional engagement with cycling as a healthy and pleasant way to commute, forms of competence would be knowing how to cycle or where to cycle. Generally, practices are not abstract scripts of actions, but they exist by its performance and until they are performed (Schäfer & Everts, 2019; Schatzki, 2001)[6]. This thesis (explicitly Article III) explores cyclists' and pedestrians' practices whilst on-the-move and refers to the understanding of practices coming from practice theory and the new mobility paradigm.

Following this new understanding of 'being mobile' and mobility practices, many new research topics and methods came along. These include, for example, participating in the pattern of movement of an individual through walking or cycling with people (as applied in this thesis, see Article II and III), time-space diaries in which participants record activities and movement or taking poetry or literature as a basis for exploring the affects and feelings of a place (Hein et al., 2008). Existing research in that field explores, for example, the sensory awareness of pedestrians (sights, touch, sound and smell) (see Degen & Rose, 2012; Vasilikou, 2016), the perception of the thermal-spatial conditions when walking outdoors (see Vasilikou & Nikolopoulou, 2020), the sensescapes[7] of the city when cycling (see van Duppen & Spierings, 2013) or walking through it (see Kelly et al., 2011) or the kinesthetic sensations of cycling (see Spinney, 2016). As argued by Büscher and Urry (2009), researching the sensescapes of people when moving is important to understand movement, because "bodies are not empirically fixed and given but involve performances to fold notions of movement, nature, taste and desire, into and through the body. Bodies sense and make sense of the world as they move bodily in and through it, creating discursively mediated sensescapes that signify social taste and distinction, ideology and meaning" (Büscher & Urry, 2009, p. 102). This sensory awareness when moving around in the city is regarded as important for a pleasant and perceived healthy commute (see Article II, III and IV).

For researching sensescapes and practices on-the-move, taking the approaches of mobile ethnography into consideration is regarded as valuable for developing the methodology of this thesis (see Article II and III), because mobile ethnography enables a deep engagement with the research subject, his/her patterns of movement and various sensescapes which are experienced as the body moves (Sheller & Urry, 2006; Büscher & Urry, 2009). Many studies following the new mobilities paradigm are rooted in ethnography and can be considered as so called "mobile

[6] For more information on practice theory in the field of mobility see for example Wilde (2013). For practice theory in the field of geography see for example Schäfer and Everts (2019).
[7] With the term "sensescapes" the attention is drawn to the sensory perceived environment, i.e. the visual, olfactory, auditive, haptic and taste experience of a specific place or environment (a singular sensescape is e.g. called "soundscape" if it refers to the auditive experience of a place). It refers to "the relationship and interaction between the sensory body and the urban environment" (van Duppen & Spierings, 2013, p. 235). For further work see e.g. Andringa et al. (2013), Degen & Rose (2012), van Duppen & Spierings (2013), van Kamp et al. (2016).

ethnographies" (Büscher & Urry, 2009). They involve a participation of the researcher in "patterns of movement [of the research subject] while conducting ethnographic research" (Sheller & Urry, 2006, p. 217). When participating in the research subjects' patterns of movement, their perceptions, their sensory awareness and their mobility practices can be investigated in relation to the passing environment. The understanding of mobility and practices following the mobilities paradigm, as described before, was shaped by mobile ethnographies "and [is] thereby intrinsically connected into practice" (Büscher & Urry, 2009, p. 111). The methodological approach of this thesis is based on mobile ethnography and practice theory, specifically considering the perceptions, practices and sensory awareness of people on-the-move (see section 3.2, Article II and III).

2.2 Perception of the environment in the field of cognitive geography

For investigating how cyclists and pedestrians perceive their environment, approaches coming from cognitive geography underpin the theoretical background of this thesis. Cognitive geography, which is closely linked to psychology, aims at exploring how people perceive their environment or symbolic representations of it (e.g. maps), how they conceptualize or emotionally respond to potential hazards or how their affection to certain places can be reflected (Lloyd, 1997; Montello, 2018). This field of geography, based on a definition by Montello (2018), focuses on "the person as a thinking, knowing and feeling agent" and understands people as "active information gatherers and processors, not passive recipients of stimuli, forces or events" (Montello, 2018, p. 5). Hence, the attention is on "understanding subjective worlds"[8] (Lloyd, 1997, p. 4). This thesis' definition of perception is rooted in the disciplinary field of geography and psychology next to the already presented mobility research and will now be presented in detail.

The nervous system of a person is responding to external stimulus. These physiological processes are called sensation. Sensations are "experienced qualitatively differently, occur in response to different types of environmental energy (e.g. chemical, thermal, electromagnetic), result from the stimulation of different types of receptors, and reflect or encode different properties of the world" (Montello, 2018, p. 8). More specifically, sensory modalities refer to vision, smell, taste, hearing, touch or kinesthesis, the latter being important for gathering body movement (Montello, 2018). In summary, perception[9] describes the process and result of receiving and interpreting this sensory information (Flade, 2013; Lloyd, 1997). For example, past experiences influence how environmental stimuli are perceived and only environmental

[8]Other well-known representatives in the disciplinary field of cognitive geography are, for example, Kevin Lynch's (1960) "Image of the city", or the work from Roger M. Downs and David Stea (1973) on cognitive mapping and spatial behaviour.

[9] In the field of cognitive geography, the term perception is usually synonymously used to cognition (Lloyd, 1997; Weichhart, 2018). Hence, this study will also refer to the term perception. Cognition can actually be defined as the larger concept which includes perception, i.e. is the interpretation of perceptions, and can be defined as the process and result of mentally creating a meaning, concept, identification and representation (Flade, 2013; Montello, 2018; Weichhart, 2018).

stimuli, which are relevant, important or have a meaning for the individual, are filtered and received; in other words, only those which are important for the current contextual goals and motivation of the individual, other stimuli are rather blocked (Weichhart, 2018). Thus, the way external stimuli are perceived is depended on how the person evaluates the stimuli, based on own experiences, values, current motivations and aims as well as his/her beliefs about spatial and non-spatial properties and relations of objects, events and places (spatial: e.g. location, distance, direction, shape; non-spatial: temporal, thematic or hedonic) (Montello, 2018; Weichhart, 2018). This thesis also draws attention to the experiences, values and aims of people on-the-move in order to explore how they perceive their environment.

It should be emphasized that the field of behavioural geography, to which cognitive geography is linked, has been criticized since its appearance (Montello, 2018). Its ability to explain human actions is argued to be limited, because people are too much seen as recipients of external stimuli and their actions are mainly explained depending on these stimuli: human actions are reduced to mechanical stimulus-reaction-relations (Weichhart, 2018). Hence, it is argued that behavioural geography is not able to explain the complexity of human actions, which is more than just a reaction to external stimuli (see section 2.1) (Weichhart, 2018). However, cognitive geography, its understanding of cognitive representation of the environment and definitions of environmental perception can still be considered as an "important desideratum of research" and is from today's perspective still relevant (Weichhart, 2018, p. 243). This thesis acknowledges the criticism of behavioural geography for explaining movement. Therefore, another theoretical perspective for studying 'doings' is applied (see 'practices' section 2.1.)[10]. However, for exploring environmental perception and air and noise pollution perception, the insights from cognitive geography are considered as valuable, explicitly if they are enriched by examining people's emotions and underpinned by risk perception theories (see section 2.3).

Emotions are of relevance for environmental perceptions, they shape the experiences and evaluations of the environmental stimuli (pleasant/unpleasant) and the way an environment is perceived (Flade, 2013; Montello, 2018). Emotions are also important for evaluating transport modes (Flade, 2013). Therefore, this thesis considers the reported emotions of people on-the-move towards their transport mode or their perceived environment (i.e. positive or negative evaluation or stated emotions, such as anger, anxiety, happiness) (Article II and III). Moreover, attitudes are important, combining what someone believes (e.g. air pollution impacts health) and what his/her affect is (e.g. worry/anger regarding air pollution) (see Article IV) (Montello,

[10] Article I, which is a literature review article, reviews studies applying mobility apps which intervene in mobility practices. The reviewed studies belong to a research field focusing on "behaviour change interventions", which refers to the term "behaviour". In accordance to the reviewed studies, the literature review in Article I uses the term "mobility behaviour". However, the thesis refers to the definition of "mobility practices" as described in section 2.1. Hargreaves (2011) discusses a similar difficulty concerning behaviour change interventions and the term "practices". He argues, that "it would be unwise […] and empirically misleading to call them [authors comment: behaviour change interventions] by another name." (Hargreaves, 2011, p. 84).

2018). This is additionally considered in this thesis for exploring perceptions and further described as part of risk perception (section 2.3). Summarizing, the way individuals perceive their environment is initially based on the primary sensory physiological processes caused by the direct stimulus and filtered by the individual; the "cognitive representation" of these stimuli is the environment as subjectively perceived by the individual (Weichhart, 2018).

The terms **perceptions**, **sensory awareness** and **practices** from a mobility and geography perceptive as used in this thesis are now clarified. The attention will next be drawn to the field of health research. Theoretical-conceptual approaches from the field of health research are considered for researching how **risks**, such as air pollution and noise pollution exposure, are perceived and coped with and how to communicate these risks.

2.3 Risk perception and protective actions

Health risks are not necessarily perceived by individuals as severe as they are claimed to be by experts and proven to be by statistics (Renn, 2014). In order to understand this discrepancy, a multidisciplinary field of research deals with this issue: risk perception (Bickerstaff, 2004). Air pollution and noise are health risks to people moving around in the city: urban residents are specifically exposed in or alongside urban traffic (Chaney et al., 2017; Cole-Hunter et al., 2012; Okokon et al., 2017; Park, 2020). Thus, risk perception and risk protection theories are considered valuable for investigating air pollution and noise exposure on-the-move.

Risk perception is based on the physical (received by own senses) and communicated (by others) information about the source of the risk, the mental processing of that information and past experiences with the risk (Renn, 2014). Environmental risks are easier perceived by people if they can sense them, e.g. hear, see, smell or feel them (see Article III and IV) (Gatersleben & Uzzell, 2000). In case of risks whose danger is difficult to evaluate, because there are no previous experiences with it nor is it possible to sense it, one is dependent on receiving external information, e.g. from peers or experts (see Article IV) (Renn, 2014)[11]. Summarizing, risk perception and responses to risks are based on analytical brain functions, grounded in the experiences of everyday life and formed in the context of social, cultural and political factors (Bickerstaff, 2004; Gober, 2018). As Renn (2014) points out, risk information has to be directly beneficial for the person and be of interest in order to stimulate an engagement with the risk. If a risk is difficult to perceive, such as, for example, the invisibility and related threats and long-term effects associated with smoking cigarettes, which is similar to inhaling polluted air, are difficult to perceive, hence, one needs to refer to information from peers or experts (Renn, 2014; Elias & Shiftan, 2012).

[11] This dependence leads to different psychological mechanisms of searching orientation. This thesis does not go into detail here, for further information see Renn et al. (2014).

There is often a discrepancy in scientific evaluated environmental risks and perceived risk by lay persons: for example, studies show that the statistically high health risk of air pollution as communicated by experts can be perceived differently by laypersons (Bickerstaff, 2004). In her review article, Bickerstaff (2004) presents different studies showing how laypersons neglect their exposure to air pollution. People are not concerned about air pollution, do not acknowledge its effects on themselves or do not consider air pollution as a problem in their home area (Bickerstaff, 2004). Gatersleben and Uzzell (2000) found out that urban dwellers in the UK worry about air quality in their home areas, however, measured pollution data does not show very serious pollution problems. A recent literature review on studies comparing perceived and measured air pollution shows that many studies found that measured air pollution and perceived air pollution are corresponding (e.g. high pollution numbers match perceived high air pollution), however, some show that air pollution has no or only a small influence on risk perception (Cori et al., 2020). This shows that there is no clear relationship between measured air pollution and perceived air pollution. Interestingly, out of the studies which found a mismatch in perceived and measured exposure, three focused on moving people and personal exposure (commuters, cyclists and taxi drivers), whereas most of the other studies showing that the perceived and measured exposure are in line did not explicitly refer to moving urban dwellers (see Cori et al., 2020). This is essential for this thesis, because it leads to the assumption that specifically people on-the-move estimate their exposure to air pollution differently than their actual air pollution measurements. Hence, investigating the relation of perceptions and measurements of air pollution on-the-move is of high interest.

As for noise, studies showed that the relation between perceived environmental noise and modeled or measured environmental noise is weak (Ueberham et al., 2019; Verbeek, 2018). Only around "one third of the variance of annoyance reaction can be 'explained' by the acoustical features" (Guski, 1999, p. 45). It was found that personal, social but also contextual factors influence noise annoyance (Fields, 1993; Guski, 1999; Verbeek, 2018). A study from Finland found that the knowledge of road-traffic noise as a health risk and positive environmental attitudes were associated with noise sensitivity and noise annoyance (Okokon et al., 2015). Similar to air pollution, recent studies have shown a bias in perceived noise exposure and the actual measured noise, suggesting that measured high sounds are not always perceived as noise (Kou et al., 2020; Ueberham et al., 2019; Verbeek, 2018) (see also Article II).

These reported differences in perceived and measured exposure may be due to the fact that from a social-cultural perspective, as for air pollution, risk perception depends on different dimensions: locality and place (sensory awareness, experienced physiological impact, (past) experiences, knowledge and local memory of a place), agency and power (be able to change situation through behaviour, powerless to influence problem) and trust and communication (trustworthiness of institutions, information/understanding of risk and trust in information sources or communicator) (Bickerstaff, 2004). Further reasons for these differences are investigated in Article II and III.

This thesis specifically sheds light on the first dimension of locality and place: sensory awareness. The importance of sensory awareness is also stressed by Gatersleben and Uzzell (2000), who found that the visual appearance of dust, the smell of exhaust fumes or the irritations to the eyes, nose or throat when expose to air pollutants reinforces perception. As shown in section 2.1, sensory awareness on-the-move has also gained attention following the new mobilities paradigm. Investigating sensory awareness of moving people is essential to explore perceived air pollution and noise exposure, related threat appraisals and coping strategies. Moreover, as also presented in section 2.2, attitudes play a role for environmental perception. For example, the attitude towards the source of the pollution (e.g. cars, traffic situation) can influence the degree to which people perceive air pollution, but also noise, to be a risk that one is exposed to (Gatersleben & Uzzell, 2000; Stallen, 1999).

As discussed, road traffic related noise and ambient air pollution in urban areas result in severe long-term and short-term health impacts and negatively impact wellbeing (Hänninen et al., 2014; Keuken et al., 2005; WHO, 2018) (see also section 1 or background in Articles I-IV). However, as previously presented, they are not always perceived as severe as they are measured (see Article II and III). Therefore, this thesis draws attention to the question how to motivate people to protect themselves from air pollution and noise en route. The Protection Motivation Theory (PMT) originally developed by Rogers (1975) and the Protective Action Decision Model (PADM) (Lindell & Perry, 2012) offer well-established theoretical backgrounds[12]. The PMT, initially developed to research the effect of fear on health perception and behaviour, explains why people undertake health impacting, risky behaviour and suggests how to motivate health promoting actions, specifically drawing attention to self-efficacy (Maddux & Rogers, 1983). The PMT was applied in studies on, for example, physical activity (Plotnikoff & Trinh, 2010), respondence to climate hazards such as floods (Bubeck et al., 2018) or in the transport sector following the Covid-19 pandemic (Barbieri et al., 2021). It can be applied for designing interventions regarding unhealthy practices, for example exposure mitigation (Becker et al., 2021). The PMT defines that the intention to protect oneself stems from cognitive beliefs: (1) **threat appraisal** (does the current behaviour lead to a severe and harmful outcome for oneself), encompassing **perceived vulnerability** and **perceived severity of risks**, and (2) **coping appraisal** (am I able to protect myself (**self-efficacy**) and do effective possibilities exist to prevent the risks (**response efficacy**)) (Maddux & Rogers, 1983; Plotnikoff & Trinh, 2010) (Fig. 3)[13].

[12] The PMT is applied in Article I and for analysing the interview data in Article VI, the PADM served as a background for developing the interview guideline in Article II and Article III. An overview of the PMT and PADM can be found as well in the respective articles.

[13] A comprehensive overview of PMT and its application for this thesis can be found in Article I and Article IV.

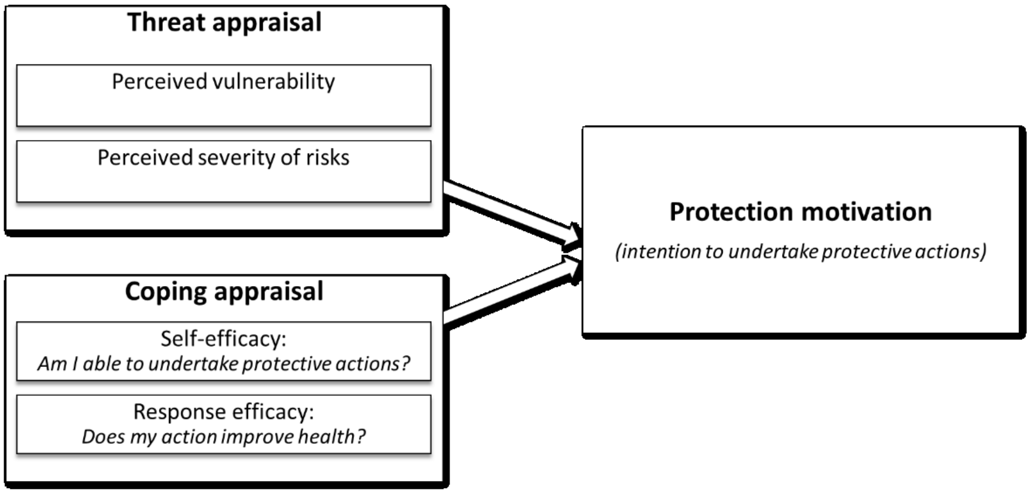

Figure 3: A simplified illustration of the Protection Motivation Theory (PMT), based on Maddux and Rogers (1983), Prentice-Dunn and Rogers (1986) and Rogers (1975)

This thesis considers the PMT as a valuable theory for analysing health protective motivations regarding air pollution and noise en route and as a background for developing communication strategies for a healthy commute (see Article I and IV). Thus, the **threat appraisal** (Maddux & Rogers, 1983; Rogers, 1975) regarding air and noise pollution for this study was defined as:

- **Perceived vulnerability**: Perception of an individual towards their susceptibility to air and noise pollution en route, i.e. the perceived probability that air and noise pollution is harmful to oneself.
- **Perceived severity**: The perceived severity of air and noise pollution on everyday routes and the perceived harm that one's everyday mobility entails.

Drawing on risk perception research (e.g. Bickerstaff (2004)), the perceived vulnerability and perceived severity of air pollution and noise can be shaped as well by sensory awareness, experienced physiological impacts, (past) experiences or knowledge of the risk as well as trustworthiness of institutions, trust in information sources or general information on the risk (Bickerstaff, 2004). These factors were used in this thesis to further explore perceived vulnerability and severity of the risks (see Article IV).

According to the PMT, the degree to which a person believes his/her action can decrease the threat is influencing protection motivation. This so-called **coping appraisal** consists on the one hand of the **self-efficacy** of a person: To what extent does a person believe that he/she is able to perform the protective action? If a person believes the protective action or avoidance strategy can be successfully performed, the more likely he/she will act accordingly (Maddux & Rogers, 1983). Moreover, the **response efficacy** is the actual effectiveness of the recommended preventive action or avoidance strategy (Maddux & Rogers, 1983). As for this thesis, the following definition of coping appraisal will be used:

(1) **Self-efficacy**: The belief that one is able to enact proposed avoidance strategies or protective actions against air pollution and noise on everyday commuting routes in the city.
(2) **Response efficacy**: Expectancy that lowering everyday exposure to air and noise pollution on commuting routes through the recommended avoidance strategies or preventive actions is possible.

The coping appraisal is regarded to be closely linked to the previously presented dimensions of risk perception. For example, the perceived ability to change the situation through protective actions or the feeling of powerlessness can impact risk perception (Bickerstaff, 2004), hence, affects the self-efficacy and response efficacy of protective actions. Additionally, the PMT assumes that a protective action is undertaken if the costs of that adaptive action (in terms of financial costs, or personal costs such as inconvenience or unpleasantness) and the rewards connected to the mal-adaptive actions are small (Prentice-Dunn & Rogers, 1986).

Sensory awareness of air pollution and noise as well as warning messages (e.g. via mobility apps) are one key focus of this thesis, hence, the Protective Action Decision Model (PADM) by Lindell and Perry (2012)[14] is additionally consulted for this thesis (Article III[15]). The PADM is another theory from health behaviour research, which is based on environmental disaster or hazard risk communication (Lindell & Perry, 2012). It specifically sheds light on a pre-decisional process, addressing the environmental and social context (called **environmental cues** and **social cues**) and "socially transmitted warnings" (Lindell & Perry, 2012, p. 617). The protective response is either the search of information, a protective action or emotion-focused coping (Lindell & Perry, 2012). The PADM has been applied for example for researching flood preparedness (Terpstra & Lindell, 2013) or as a framework for explaining adoptions of electric vehicles during smog (Liu et al., 2019). The environmental cues (sights, smells, sounds) and social cues (fellow people) as well as information (warning messages) or perception of stakeholders (e.g. authorities, media, scientists/experts) are important for threat perceptions and motivating protective actions. They also relate to the self-efficacy and coping appraisal as in the PMT (Lindell & Perry, 2012).

Summarizing, the experiences of the commute (e.g. environmental cues, social cues, attitudes/emotions regarding transport modes or routes, cf. section 2.1), related mobility practices (e.g. protective practices, cf. section 2.1,) and the perceptions, such as sensory awareness of the environment on-the-move (perception of a risk, cf. section 2.2), are important for risk perception and the motivation to protect oneself (see Article II and III). Moreover, also stakeholders or information sources play a role (cf. section 2.3). These different theoretical

[14] Note that this refers to a modified version of the PADM, developed by the original authors of the PADM. For further information on their first mentions and version of the PADM see Lindell & Perry (2004).
[15] Mainly in Article II/III, as a basis for structuring the go-/ride-along interview, which aimed at researching sensory awareness and social cues.

backgrounds enrich this thesis' approach to investigate environmental health risk perceptions on-the-move. They also propose a valuable background for researching how to inform about healthy mobility and health-protective practices en route (see Article I and IV, the latter giving more background information on advantages and challenges of the PMT).

2.4 Risk communication and environmental health literacy

The previous sections have presented the theoretical background for researching commuters' perception and practices on-the-move and link these theories with health protection theories. These theories target the individual level of risk perception and protective practices; however, they do not draw attention to collective protective actions and do not give indications on how to effectively communicate en route health risks. One aim of this thesis is to explore possible information and communication options for a healthy commute (see Article IV), hence, a concept for environmental health communication is consulted. This is specifically applied in Article IV to explore how cyclists and pedestrians want to be informed about air pollution and noise exposure. Thereafter, the concept of Environmental Health Literacy (EHL) is applied. EHL is an action-oriented concept and provides structures on how to increase awareness and support people to take action, having its roots in risk communication, health communication and participatory communication research (Hoover, 2019). Whereas the PMT or PADM have given background in how individuals protect themselves from a risk, they do not draw attention to the structural problems underlying a risk. The EHL also incorporates the collective actions, by drawing attention to community creation. Thus, the EHL highlights how the individual can influence the community to actually tackle the risk. Environmental exposure, such as air pollution, is often a community-wide problem and can barely be solved by the individual; the concept of EHL can address the needed community engagement (Finn & O'Fallon, 2017; Gray, 2018). As the final question of the thesis draws attention to information and communication strategies, it does not only refer to the individual perceptions and practices, but considers collective actions. Hence, the concept of EHL is considered for examining air pollution and noise communication (see Article IV or section 3.5).

The EHL concept has three dimensions: (1) awareness and knowledge, (2) skills and self-efficacy and (3) community change (Gray, 2018). Based on Bloom's (1956) taxonomy of educational objectives, Finn and O'Fallon (2017) define six stages of EHL, namely: **recognition**, **understanding**, **application**, **analysis**, **evaluation** and **creation**. When becoming environmentally health literate, a person progresses through each stage, meanwhile, gaining knowledge and taking action (Finn & O'Fallon, 2017). Firstly, the severity of a certain risk, i.e., pollution, and its impact on health is recognized and understood. Subsequently, the EHL increases, hence a person can apply, analyse and evaluate information regarding that risk and gains skills to take action. With this increased self-efficacy, one feels that health-protective actions can be undertaken and exposure reduced (Gray, 2018). Self-efficacy is also a central part of the PMT, showing the need to increase self-efficacy to motivative health protective actions (cf. section 2.3). Ultimately, collective actions for reducing pollution can be undertaken, e.g. engaging in policy or in the community (Gray, 2018). This information exchange is beneficial, because different community stakeholders can tackle environmental problems collectively (Hoover, 2019). For example, presenting cyclists or pedestrians information on air pollution and noise exposure en route can increase awareness and knowledge (step 1). As this knowledge develops, in the next step they would be able to find less-polluted routes or undertake protective actions themselves (step 2, skills and self-efficacy). By approaching step 3, they would then be able to evaluate their knowledge and skills and communicate it to others. Hence, engage in community (community change). Drawing on these steps, this thesis takes the concept of EHL for developing and structuring communication strategies as suggested by the participants, who participated in the research of this thesis (see Article IV for more discussions on advantages and challenges of the concept of EHL, and section 3.5 for the application of the EHL concept).

3. Research design and applied methods

One aim of this thesis is to examine measurable objective exposure to air pollution and noise and subjective perceptions on-the-move. Therefore, this thesis focuses on the environment that cyclists and pedestrians pass through every day, as well as their movement as such. The other aim is to investigate how cyclists and pedestrians want to be informed about a healthy and pleasant commute including risks from air pollution and noise. Hence, cyclists and pedestrians are consulted as experts of their commute. These research aims (cf. section 1.2) can best be addressed by a combination of qualitative and quantitative methods: a mixed-methods design.

Both qualitative or quantitative methods can stand alone and refer to a certain research paradigm; by mixing both approaches, a quantitative measurable phenomenon can be put in relation to the qualitative side of understanding its underlying meaning (Kuckartz, 2014). Mixed-methods designs offer new approaches to generate research questions and provide comprehensive answers (Johnson et al., 2007). Some mixed-methods designs are straightforward – sequential or parallel[16] – others are more complex and integrate different methods in more than one stage of the research (Kuckartz, 2014). The research aims of this thesis demand for a complex design. In order to prevent a lack of clarity in complex mixed-method designs, it is important to clarify the methods' implementation, priority, and theoretical backgrounds (Kuckartz, 2014). To address this, the following section will present the implementation of the applied qualitative and quantitative methods. The theoretical backgrounds for the study design are coming from ethnography, practice theory and health theories. They have been presented in the previous section 2.

This thesis complements go- and ride-alongs (qualitative) with wearable sensors (quantitative) and focus groups (qualitative). The qualitative methods have a priority and are applied to investigate the exposure experiences and practices of people on-the-move and the information required to undertake a healthy and pleasant trip. To consider the movement of the research subject, a mobile qualitative approach (go- and ride-alongs) was used: the research subjects were accompanied on foot or by bicycle and meanwhile interviewed. By interviewing people on-the-move it was possible to dive deep into their everyday mobility practices and en route experiences (section 3.3). Moreover, focus groups were applied to research how exposure information should be designed and what collective actions derive from air pollution and noise risk communication (section 3.5). In qualitative research, the people under investigation are regarded as experts of their life and experts of the questions under research (Lamnek & Krell,

[16] Mixed-method research designs can either be concurrent/parallel (QUALITATIVE + QUANTITATIVE), sequential (QUALITATIVE→QUANTIATVE; QUANTIATIVE→QUALITATIVE) or complex (integration of QUALITATIVE and QUANTIATIVE methods in different stages of the research process). The emphasis of the chosen paradigm can either have an equal status (both equally important) or a dominant status (either QUALITATIVE and quantitative or QUANTITATIVE and qualitative, hence, one is dominant (QUAL, or QUAN), while the other (qual, or quan) has lower priority) (Johnson & Onwuegbuzie, 2004; Kuckartz, 2014).

2016). Qualitative methods are essential in the field of human geography and have also gained attention in the field of health geography, risk perception research and travel behaviour studies (Baxter, 2018; Bickerstaff, 2004; DeLyser et al., 2010; Mars et al., 2016). Qualitative research in human geography recognizes "the complexity of everyday life, the nuances of meaning-making in an ever-changing world, and the multitude of influences that shape human lived experience" (DeLyser et al., 2010, p. 5). The aim of this thesis is to in-depths explore these lived experiences of cyclists and pedestrians; hence, the qualitative approach had priority.

To put this in relation to the quantitative measurable phenomena of air pollution and noise, this thesis considers simultaneously the dynamic measurable air pollution and noise exposure when moving in the city. Exposure measurements were applied. The spatiotemporal patterns and dynamic changes of exposure while moving demand for mobile measurements by wearable sensors (Helbig et al., 2021; Larkin & Hystad, 2017; Schlink & Ueberham, 2020; Snyder et al., 2013). It is promising to use wearable sensors for individual-based measurements of environmental stressors to "overcome the microenvironment and land-use-concepts that are not individual-based" (Schlink & Ueberham, 2020, p.4). Combining wearable sensors with on-the-move survey techniques is considered promising (Schlink & Ueberham, 2020). For this thesis' research aim the measurements receive a lower priority. They are supporting the interpretation of the qualitative data rather than being investigated in itself.

A systematic **literature review** (section 3.1) was conducted followed by an **empirical data gathering** phase (section 3.2). The empirical phase comprised three stages: **qualitative go- and ride-along interviews** complemented by **wearable sensors** (section 3.3) and **GPS-tracking** and questionnaires (section 3.4) followed by **focus groups** (section 3.5) (Fig. 4).

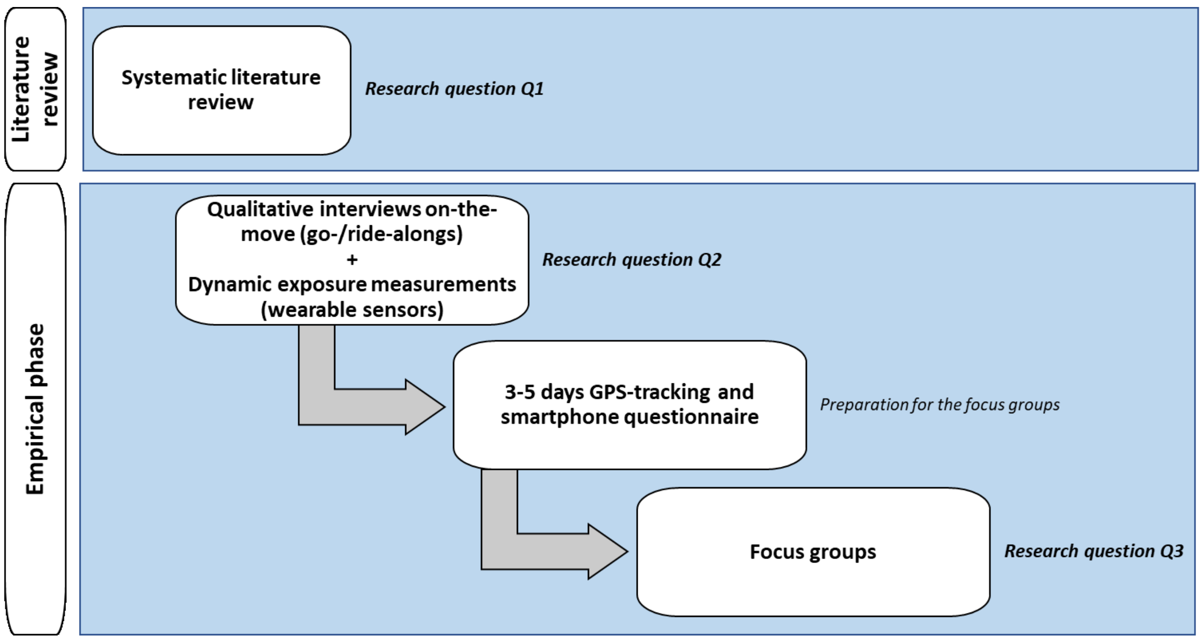

Figure 4: Study design of the mixed-method approach

With each method one of the three main research questions is explored (tab. 2). In the following, the methods applied in this thesis will be presented in detail. Further descriptions and reflections of the methods can be found in the articles (see tab. 2) and in the reflection at the end of the thesis (section 5.4).

Table 2: Overview of the research questions and the focus of the respective studies, the methods used and the related articles of this cumulative thesis

Research question	**Focus of the study**	**Method**	**Article**
Q1	Identify current literature applying mobility apps regarding the information the applied apps comprise	Literature review *(section 3.1)*	I
Q2	Investigate people's perceived exposure en route, experiences of the route environment and commuting practices and simultaneously measure their exposure to air pollution and noise	Go- and ride-alongs Wearable sensors *(section 3.3)*	II + III
Q3	Examine how people want to be informed about air pollution and noise en route and explore what aspects would support a healthy but also pleasant commute in urban areas	GPS-tracking and questionnaire Focus groups *(section 3.4/3.5)*	IV

3.1 Literature review

For investigating research questions Q1, a systematic literature review was conducted (Article I). The added values of a literature review are to identify gaps in literature, present new research agendas or to result in conceptual models based on the reviewed literature (van Wee & Banister, 2016). The aim of the literature review was to identify to what extend mobility apps applied in recent empirical studies address health components and to unravel if air pollution and noise – or other health components – are addressed in the mobility apps. Furthermore, it was investigated how mobility apps could inform about mobility-related health topics. The focus was on studies applying mobility apps which aim at intervening in current mobility choices. The reason for choosing mobility apps which intervene in mobility choices was because these apps usually integrate different information (on e.g. environmental impacts or health). Moreover, they are usually developed to support the user to undertake environmentally friendly, healthy or cost-effective mobility choices (see Article I). Hence, the mobility apps in the reviewed studies provided certain information or 'behavioural change techniques' to support the app user to change their mode or route. Usually, they aimed at inducing sustainable mobility choices (Article I). This was of interest for this thesis' research question on how to inform cyclists and pedestrians about healthy and pleasant mobility choices and gave a valuable background of the current state of research regarding mobility apps and health.

The literature review was based on the PRISMA guidelines for literature reviews. The PRISMA guidelines systematically guide the researcher through the reviewing process and makes the reviewing process transparent (Moher et al., 2009). For in-depths information about the literature review process see Article I (section 4.1). After identifying and screening relevant articles, the included literature was examined concerning the information they address, taking mobility-related health components based on Nieuwenhuijsen and Khreis (2019) and van Wee and Ettema (2016) as a background. A special focus was set on identifying if air pollution and noise information were addressed. Based on the reviewed studies and PMT (see section 2.3) the literature review resulted in the development of a conceptual framework. The literature review process and its results are presented and discussed in Article I. Additionally, the literature review provided a valuable background for the empirical phase, specifically for the focus groups, and enriched the discussion about how to communicate healthy and pleasant routes using mobility apps (see Article I and section 5.2).

3.2 Overview of empirical phase

The empirical phase consists of three stages which build on one another (see Fig. 4). The participants undergo each stage: First, qualitative interviews on-the-move, so called go- and ride-alongs, complemented by wearable sensors were conducted. Second, the same participants were asked to track their commuting route for three till five days using a tracking app with integrated questionnaires. Third, after 8-10 participants have taken part in the first two stages, they were invited to the third stage, the focus group.

The empirical phase took place in Berlin, the capital of Germany. Berlin has 3,7 Million inhabitants (2021) and covers an area of 891,7 km². Berlin has a low topography and is located between a continental and oceanic climate, having good conditions for cycling and walking (SenUVK, 2021). Moreover, Berlin is one of the greenest cities in Europe with high values of vegetation on the neighbourhood level (Lakes et al., 2013). One main river (Spree) and some smaller rivers flow through the city. Some areas in the city are densely built areas, specifically the city centre has reported low environmental quality regarding noise and vegetation (Lakes et al., 2013). Berlin has passed a mobility act in 2018, which specifically considers the promotion of cycling and walking in the city (SenUVK, n.d.) and has published strategies to lower noise (SenUVK, 2019b) and air pollution (SenUVK, 2019a). These facts and developments make it an interesting city to research cycling and walking in combination with air pollution and noise.

Participants were recruited through social media, newsletters, flyers, direct contact with offices and online neighbourhood networks as well as through snowballing. Therefore, a diverse recruiting was ensured, reaching people with different life situations and different commuting routes. As an incentive, participants were offered personal feedback on air pollution and noise. Requirements for taking part were commuting to work or educational site (e.g. university) with a bicycle, on foot or by public transport and living and working/studying in Berlin. In total, 28 people participated in the first stage of the empirical phase (go- and ride-alongs). The participants were selected, so that there was an equal gender and age ratio in the sample. Out of these 28 participants, 20 people also participated in the focus groups (third stage). Due to the the outbreak of the Covid-19 pandemic[17] in early 2020, the empirical phase was interrupted. Therefore, the first 10 participants who underwent the three stages participated in October-December 2019 before the Covid-19 pandemic outbreak. The other 18 participants were recruited and participated after the outbreak, from August-November 2020. Possible effects of the Covid-19 outbreak on the data gathering and results as well as reflection on the recruiting strategy and sample are discussed in section 5.4.

In general, all interviewees had a driver's license and a bicycle available, most also had a public transport ticket and some also used car-sharing. A sample overview can be found in Article II and IV. Each method of the empirical phase will now be described. Further information about the methods and data analysis can be found in Article II and Article III (go-/ride-alongs and wearable sensors) and Article IV (focus groups).

3.3 Go- and ride-alongs complemented by wearable sensors

For addressing research question Q2 and as a preparation for answering Q3, go- and ride-alongs complemented by wearable sensors were applied (see Article II and III). The perceived exposure, sensory awareness and protective practices were explored and enriched by measurements of air pollution and noise on-the-move.

Go- and ride-alongs, coming from the research fields ethnography, anthropology and geography, are mobile, on-the-move qualitative interviews during which an interviewer accompanies the interviewee (King & Woodroffe, 2017). This can be done on foot (in this thesis referred to as go-along, also called walk-along or walking interview), on wheels, for example by bicycle (ride-alongs), or both (King & Woodroffe, 2017; Kusenbach, 2003). Therefore, the interviewers „– through asking questions, listening and observing – actively explore their subjects' stream of experiences and perceptions as they move through, and interact with their physical and social environment" (Kusenbach, 2003, p. 463). Go- and ride-alongs can be regarded as mobile methods. Mobile methods, also applied in studies referring to the new mobilities paradigm, are rooted in the research field of mobile ethnographies (see section 2.1), making it possible to research the sensing body on-the-move, the "sensory experience, embodiment, emplacement" (Büscher & Urry, 2009, p. 110). Go- and ride-alongs are interactive methods and valuable for discussing with the interviewee their perceptions, how

[17] For more information on the Covid-19 pandemic see the official website of the WHO: https://www.who.int/emergencies/diseases/novel-coronavirus-2019

perceptions change as the body moves through space, as well as reveal the interviewees interpretations of the physical, built and the social environment (Carpiano, 2009; Evans & Jones, 2011; King & Woodroffe, 2017; Kusenbach, 2003). Moreover, accompanying the research subject on-the-move is a valuable way of examining practices in real time and in space (Carpiano, 2009; Kusenbach, 2003). Hence, the interviewee's *saying* and *doings*, referring to practice theory (section 2.1), can be observed and discussed with the interviewee in situ (Kühl, 2016; Schäfer & Everts, 2019). Being on-the-move is different compared to being stationary, hence, mobile methodologies and methods, which make the movement part of the research process, are valuable to study mobility (Hein et al., 2008). For investigating the movement of people, applying mobile methods seems crucial. Go- and ride-alongs have been applied in mobility research, for example for exploring embodied experiences while cycling (see van Duppen & Spierings, 2013) or walking (see Kelly et al., 2011 or Pooley et al., 2013). For this thesis, go- and ride-alongs are considered useful to explore cyclists' and pedestrians' perceived personal exposure on-the-move and their sensory awareness, i.e. how they see, hear and smell their environment whilst cycling or walking. Moreover, go- and ride-alongs are considered useful for observing and discussing protective practices en route and discuss experiences, aims and motivations of route choices. Article II (section 4.2) provides further insights into go- and ride-alongs and discusses benefits and obstacles.

The go- and ride-alongs were complemented by **wearable sensors** measuring air pollution and noise on-the-move. Recently, pollution monitoring has given the movement of people attention, which is due to new technological developments in this field. This 'changing paradigm in pollution monitoring' is based on the increasing usage of portable pollution sensors (Snyder et al., 2013). These are low-cost and can easily be used and carried by laypersons, allowing participatory monitoring of health impacting pollution (Helbig et al., 2021; Larkin & Hystad, 2017; Snyder et al., 2013). As a result, local pollution and its variations can be recorded, meeting the demand to address "spatial nonstationarity", i.e. acknowledging that the relationship between environmental factors and health can vary across a study area (Kwan, 2021). Wearable sensors enrich the go- and ride-alongs with on-the-move exposure measuring (see Article II and III).

Sample

As describes in section 3.2, the sample comprised 28 adults living in Berlin, Germany, who cycle, walk or take public transport to work on a regular basis. Three pre-tests (two by bicycle, one by foot and public transport) were undertaken with participants not included in the sample. 21 go- and ride-alongs were conducted by bicycle, five on foot (and public transport, i.e., bus, commuter train or subway) and two by bicycle and commuter train (see Article III for an overview).

Procedure

After getting in contact with people who were interested to participate, the participants could suggest time and place after work for the introductory interview and the following go- or ride-along. The introductory interview was done sedentary and the place was chosen by the interviewee, for example in a café, at work or on a bench. Having an introductory interview helped the interviewee to get familiar with the interview situation and with the interviewer[18]. The guideline of the introductory interview addressed the interviewee's health concerns and awareness of air pollution and noise en route. The aim was to receive a first impression of the forthcoming route and the interviewee's perceptions. The interviewee was asked to describe the forthcoming route and important route aspects. This was necessary to a.) be prepared for the upcoming route and possible challenges en route (e.g. streets without cycling infrastructure or high traffic volume, length of the route, destination), b.) stimulate the interviewee to be prepared to evaluate and describe their perceptions along the upcoming commuting route and c.) have background information to which the interviewer could refer to during the go- or ride-along. For example, during the go-/ride-along questions could be asked, e.g. "during the introductory interview you talked about [a street/area/…], is this the [street/area/…] you meant?".

Directly after the introductory interview, the interviewer accompanied the interviewee by bicycle or on foot (incl. public transport) on his/her way home from work. Meanwhile, a semi-structured interview guideline guided the on-the-move interview. The questions of the interview guideline stimulated the interviewee to actively think about and describe their perceptions, experiences, route choices and their practices en route, but were still open so that the interviewee could mention important upcoming and unforeseen aspects him-/herself. Using semi-structured interview formats is "potentially more conversational in nature" and can improve the conversation during "any rare lull periods" (Carpiano, 2009, p. 11). The interview guideline was open to add ad-hoc questions if sudden incidents happened en route. The guideline can be found in Appendix B and is further described in Article II and III. The guideline was well known by the interviewer due to several pre-tests (as suggested by King and Woodroffe (2017)) and attached to her bicycle during cycling or at hand during walking. Interviewee and interviewer were wearing a microphone attached to a recorder and clipped to the collar. Hence, the interview could be recorded even when moving fast and whilst passing the environment under investigation (Kusenbach, 2003). Individually attached microphones and voice recorders also lowered the physical risks of traffic injuries, which needs to be considered during go- and ride-alongs (King & Woodroffe, 2017). Important observations were recorded by the interviewer using the voice recorder and by taking pictures en route.

[18] "The interviewer" in this thesis (and in the articles) refers to the author of this thesis, who is the only interviewer in all go- and ride-alongs and as well the sole moderator of the focus groups.

Whilst accompanying the interviewees, particulate matter (counting of particles smaller than 2.5µm per cubic foot, measurement interval: minute; in the thesis referred to as 'particulate number count' (PNC)) were recorded by the air quality monitoring device DylosLogger 1700, which was carried by the interviewer. Noise was measured including GPS-coordinates (dB(A) every 2 seconds, device: Motorola G3 with external microphone and pre-installed sensing application, developed by Ueberham et al. (2018)). The devices were applied and validated in previous studies (see Ueberham & Schlink 2018; Ueberham et al. 2019), tested during the pre-tests and tested against equal devices beforehand. The Motorola G3 tracked also GPS and the wearable sensors had time stamps. The exact time when the go- and ride-along started was noted so that the qualitative interview data could later be attached to the measurement and GPS-coordinates. The wearable sensors and interview guidelines were tested and improved following the pre-tests. For more information on the procedure see Article II and III.

Data analysis

The go- and ride-along interview data was complemented by the wearable sensor measurement data in two steps. First, the recordings of the go- and ride-alongs were transcribed using the transcription software f4, including real time stamps. The interview transcripts were then analysed applying qualitative content analysis following an inductive-deductive approach (Kuckartz, 2020). Main codes[19] were created deductively based on existing literature and the theoretical background. Specifically, based on the assumption that sensory awareness, environmental or social cues, influence risk perception and protective practices and influence how mobility is experienced (see section 2). The coding was open to new and unforeseen themes, so codes were also built inductively out of the data. As the focus was on perceptions and practices on-the-move, only statements were coded with spatial relation, referring to the immediate environment[20]. The qualitative data analysis software MAXQDA2020 (version 20.4.1) was used. The coding resulted in:

(a) **sensory awareness**, i.e. statements related to perceived sounds, perceived air/smells and visual experiences
(b) **protective practices**, i.e. practices undertaken on-the-move
(c) **perceived physical health and wellbeing** in situ
(d) **affective/emotional experiences**, i.e. a pleasant or unpleasant feeling in situ (often coded as a supplement to the codes of sensory awareness: when someone stated he/she negatively perceived noticeable air pollution, it was coded as "unpleasant" and

[19] In qualitative data analysis, "codes" refer to categories which are built when analysing the transcripts. They can be either coming from literature and theoretical background (deductively) or out of the data (inductively). Statements or sentences of the transcripts are assigned to a specific code, hence, codes "systematize and assign meanings to [the] data material" (Kuckartz & Rädiker, 2019, p. 19).
[20] Note that the interview guideline was developed so that the answers usually referred to the immediate environment. Hence, most of the statements referred to it.

"noticeable air pollution", when someone talked about the calming effects of seeing nature, it was coded as "pleasant/relaxing" and "seeing nature")

(e) **observations of the environment** by the interviewer, i.e. important external situation such as, for example, crowded area, intersection, side roads or water/greenery

In a second step, the coded transcripts of the go- and ride-alongs were matched with the wearable sensors data. As shown in Article II (section 4.2), this phase of data analysis applied an integrated mixed-methods approach, analysing the data by "comparison" and "assimilation" (see Steinmetz-Wood et al., 2019). First, all measurement data of the wearable sensors (PNC, noise and GPS-coordinates) were merged. The measurement data was then visualized using the software QGIS[21] and integrated with land use data from the city of Berlin (source: Geoportal Berlin/FNP, https://fbinter.stadt-berlin.de/fb/index.jsp). For data privacy the first and last meters were cut off. For comparing the measurement data with the qualitative interview data, the measured PNC was translated into seven percentiles for each route[22] using QGIS, from "1 – comparably extremely low" till "7 – comparably extremely high". Noise was evenly divided into eight classes (46 dB(A) - 50 dB(A), …, 81 dB(A) - 85 dB(A)).

In a next step, the measurement data and selected sub-codes from the interview transcripts were merged by using time stamps. Especially value-oriented[23] codes were considered, i.e. *unpleasant*, *stressful* and *unattractive* or *pleasant*, *relaxing* and *attractive* (see assimilation as a strategy of mixed-method data analysis (Steinmetz-Wood et al., 2019)). These were chosen because they refer to how the participants evaluate their in-situ environment. Furthermore, the sub-codes *noticeable air pollution*, *good smell/air*, *noise* and *quietness* and the code *protective practices* were merged with the wearable sensor data. The data was then integrated and visualized in the software QGIS. Integrating qualitative data into Geographic Information Systems (GIS), so called "qualitative GIS", offers great potential to visualize and analyse qualitative data with spatial relation and investigates the complex interrelationships of people and space (Cope, 2009; Kwan & Ding, 2008). As a result, quantitative measurements could be compared with the participants' qualitative evaluations of the environment and their practices en route. These were interpreted amidst the situational context by consulting observations, pictures, the basemap and land use data.

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[21] QGIS refers to a Geographic Information System (GIS) software for analysing, visualizing, editing and exporting spatial data.

[22] Due to high differences of measured PNC depending on time of the day, weather situation and season, the PNC was translated into percentiles for each route, referring to a rather qualitative evaluation. Hence, the measurements of the participants were comparable with one another when merged with the qualitative interview data. The goal was to understand if people on their respective route perceive differences in high and lower pollution en route. This approach was considered valuable, because pollution peaks on the respective routes could be still compared to other participant's peaks and perceptions en route, regardless of variations.

[23] Value-oriented codes refer to codes, which represent the value or evaluation of the respective situation as stated by the participant (e.g. pleasant, unpleasant). Transforming qualitative data into value-oriented codes, to which quantitative measurements can relate to (high polluted, low polluted - so called "assimilation strategy"), is beneficial for analysing data gathered through a mixed-methods design (Steinmetz-Wood et al., 2019).

As a final step, the wearable sensor measurements were integrated into the qualitative data analysis software (MAXQDA2020) by creating two new codes (*measured air pollution* and *measured noise*) with their respective percentile (for example “7 – extremely low”, or “46-50 dB(A)”) being a sub-code. The transcripts were then again coded and the respective exposure measurement code was assigned to the statements, in which interviewees evaluated their environment regarding *affective/emotional experience* and *sensory awareness*, i.e. *noticeable air pollution*, *good smell/air*, *noise* and *quietness*. The data analysis integrated the data in both ways: the qualitative data in the quantitative data analysis software and vice versa (Fig. 5). The retrieved codes can be found in the code book in Appendix D.

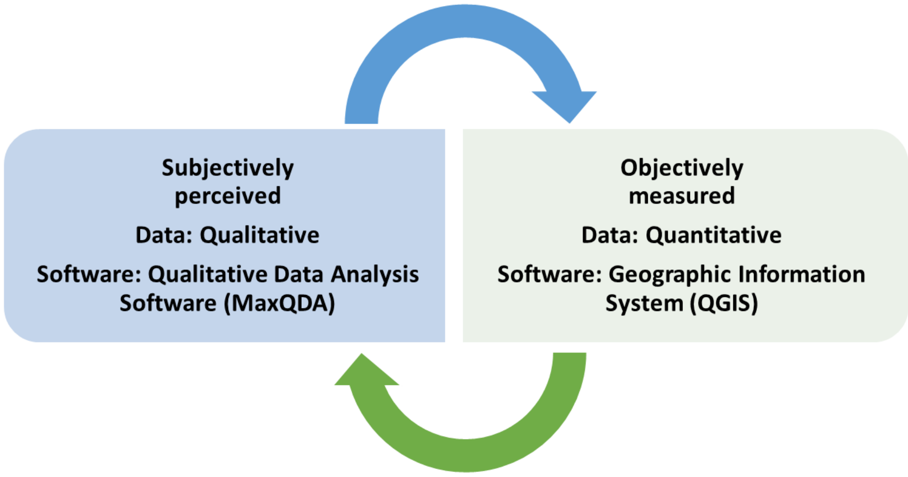

Figure 5: Illustration of the integration of analysing qualitative interview data and quantitative measurement data

3.4 GPS tracking and questionnaire

Directly following the go- and ride-alongs, the interviewees were asked to download the DLR MovingLab smartphone application[24]. The DLR MovingLab app is a tracking app, which automatically detects the transport mode, tracks the route and provides the opportunity to include a short questionnaire. After participating in the go- and ride-along, the participants were asked to independently track their commuting route to work and back for five days (due to home office as a result of the Covid-19 pandemic, some only tracked two till three days). They were asked to try out different routes to/from work. After each route, a short questionnaire showed up. It comprised questions regarding perceived air pollution exposure, noise exposure, impacts on health and stress experienced on the route. The questionnaires were supposed to frequently confront the interviewee with air pollution and noise exposure perception following the weeks after the go- and ride-alongs, raise awareness and keep the interest regarding these topics high. This attention to air pollution and noise en route served as a preparation for taking part in the focus groups. Moreover, the tracked routes were presented in the focus groups on a table with

[24] For more information see: https://movinglab.dlr.de/

a screen[25] or via PowerPoint to the participants, hence, served as visualization and stimuli for the focus group (for information on stimuli in focus groups see Schulz et al. (2012)). The independent tracking data was solely used as a stimulus for the participants, was not analysed and is not presented as part of this thesis.

3.5 Focus groups

In the final step of the empirical phase focus groups were conducted, involving the participants who participated in the go- and ride-alongs and independent GPS tracking. A focus group is a qualitative research method, which has "a focus on specific issues, with a predetermined group of people, participating in an interactive discussion" (Hennink, 2014, p. 2). In this interactive discussion, one interviewee's statement can stimulate others to have new ideas or opinions (Schulz, 2012). Focus groups have been used as a qualitative inquiry in human geography (Cloke et al., 2004). A focus group approach is considered suitable for this thesis, because focus groups consist of preselected participants who have shared experiences and whose experiences refer to the research issue, there is a specific topic discussed in detail and there is a range of perspectives about a specific topic which is meant to be uncovered (Hennink, 2014; Schulz et al., 2012). The invited participants of the focus groups shared experiences: all had taken part in the go- or ride-along, the air pollution and noise measurement and the independent MovingLab GPS-tracking. Based on shared experiences, a focus group is useful to create innovative ideas, discuss perceptions that the interviewees agree (or disagree) on and create solutions of a problem (Schulz, 2012). Hence, "the essential purpose of focus group research is to […] gain an understanding of the issues from the perceptive of the participants themselves" (Hennink, 2014, p. 2). For answering research questions Q3, which aims at exploring how people want to be informed about air pollution and noise en route, focus groups are considered as suitable.

Sample

In total, 20 participants participated in three focus groups, six till eight participants each. These 20 participants are out of the 28 who had taken part in the go- or ride-alongs with wearable sensor measurements (section 3.3) and independent MovingLab GPS tracking (section 3.4). For further information on the sample see section 3.2, section 3.3 and Article IV. Due to the Covid-19 pandemic, the first focus group (before the Covid-19 pandemic) took place on-site, the second focus group was partly on-site with two participants joining online and the third focus groups was completely online. Effects of the Covid-19 outbreak on the empirical phase are discussed in section 5.4.

[25] The DLR MovingLab includes a stationary Lab, on which the tracked routes of a campaign can be visualized on a digital touchscreen table. This has been used for the first focus group before the Covid-19 pandemic (section 3.5) and was considered as valuable for discussing the tracked routes in a focus group discussion (see section 5.4). Due Covid-19 restrictions the Lab could not be used for the later focus groups.

Procedure

All three focus groups were digitally recorded and important statements and observations were noted by the interviewer. The interviewer guided the focus group discussions giving stimulus and input based on an interview guide (see Appendix C or Article IV) and made sure that everyone had a saying, while still staying in the background during discussions (see Schulz, 2012). The focus group guideline followed three main topics, namely (a) experiences and perceptions of air pollution and noise during and following up the go- and ride-alongs and the MovingLab tracking, (b) receiving feedback of exposure measurements (peaks and low exposure en route) and discussions about what impact this might have on future route and mode choices or practices en route and (c) exchanging ideas on how to be informed about a healthy and pleasant trip (see Article IV for more information).

The interview guideline followed these topics chronologically but left plenty of space for the discussion. Part (a) and (b) addressed the Protection Motivation Theory (PMT) and Environmental Health Literacy (EHL) (section 2.3 and 2.4). They aimed at revealing participants' motivation to undertake protective practices following the go- and ride-along and their recognition and evaluation of air pollution and noise risks en route. The participants exchanged experiences made during the go- or ride-alongs, the exposure measuring and MovingLab tracking. As a stimulus, a flipchart with the option to rank exposure perceptions was provided (see Kühn et al., 2011). Moreover, pictures from the go- and ride-alongs were shown and guiding questions asked, which altogether aimed at stimulating a narrative about new understandings, recognition and evaluation of air pollution and noise risks. Furthermore, this phase aimed at investigating changes in perceived severity and perceived vulnerability to noise and air pollution. Consequently, it was explored if participants implemented or are motivated to implement new practices, preventive actions or changed routes.

During part (b) the participants received feedback on their measured exposure. As argued by Brody et al. (2014), informing participants about personal monitored exposure can lead to individual and community empowerment, motivate to reduce or avoid exposure and can improve environmental health literacy. During part (b), participants received brochures with exposure information, referring to the measurement data of the wearable sensors. It included graphs and a map which indicated higher exposure en route compared to other route sections (using color coding, different symbol sizes). Moreover, a short text-based description of exposure in general and peak exposures en route was provided. Ultimately, avoidance strategies were suggested, and further information was given (e.g. environmental agency/WHO websites).

In part (c), the focus groups explored communication strategies and information needs. Based on their shared experiences, the group discussed information provision options regarding healthy and pleasant routes. For this, stimulus material (pictures) was provided. Showing stimulus material can be inspiring for the participants to creatively develop ideas based on the stimuli (Mack & Tampe-Mai, 2012). Examples of pollution communication options (e.g. smartphone apps, digital signs in the city, newspaper) were presented, which stimulated an open discussion on how the participants want to be informed. The focus group interview guideline is attached in the Appendix C.

Data analysis

The recorded focus group discussions were transcribed using the software f4 and analysed with MAXQDA2020 (version 20.4.1). For analysing the data, a thematic coding was applied, identifying and analysing themes in the data (Kuckartz, 2020). The coding followed an inductive-deductive approach. Categories and codes based on the theoretical background were created beforehand and the transcripts analysed accordingly. Meanwhile, the coding system was open to new and unforeseen aspects, so that codes were also inductively created out of the data (Kuckartz, 2020; Schulz et al., 2012). The categories deductively developed were based on the theoretical background: (1) Protection Motivation (components of the PMT) and (2) Information sources and communication of risks (the codes referring to the stages of EHL) (see section 2.3 and 2.4). The codes were then retrieved out of the data inductively. During the analysis, another code was inductively developed: information denial. The transcripts were then again coded by the final code-system in several iterative rounds of coding and analysed using MAXQDA2020 (see Kuckartz, 2020). Further descriptions of the coding system can be found in Article IV and the code book in Appendix E.

The mixed-methods design of this thesis has integrated both qualitative and quantitative methods in different stages of the research process. The mixed-method approach, its benefits and limitations are described in the respective articles and also reflected upon in section 5.4. In the following, the articles of the thesis will be introduced and presented.

4. Publications of the cumulative thesis

The following section presents the four research articles of this thesis. The articles are the main part of this thesis and address this thesis' research aims and questions (section 1.2). Three articles are published in peer-reviewed journals and one is submitted to a peer-reviewed journal[26]. A short introduction will be given before each article.

The first article, Article I, is a literature review which investigates to what extent the topic health, specifically air pollution and noise, is included in mobility apps applied in literature (research questions Q1). Following this, Article II and III present the methodological approach and findings from the first stage of the empirical phase: the go- and ride-alongs complemented by wearable sensors, investigating perceived and measured exposure, sensory awareness and protective practices (research questions Q2). Finally, Article IV presents the last stage of the empirical phase, the focus groups, and discusses communication and information possibilities regarding air pollution, noise and pleasant and healthy route aspects (research questions Q3). Article II and III give insights into what is needed for a healthy and pleasant commute from participants' perspective. Article I and Article IV add to this by framing the thesis and addressing the topic of exposure information provision. They refer to the aims and findings from Article II and III. Following this section, in the final section 5, implications and future research directions derived from all four articles and this thesis as a whole will be given and a conclusion will be drawn.

[26] At the time the thesis was handed in the manuscript was submitted and minor revisions requested.

In the following, the four research articles will be presented in detail:

Article I	***Marquart, H.****, & Schuppan, J. (2022). Promoting Sustainable Mobility: To What Extent Is "Health" Considered by Mobility App Studies? A Review and a Conceptual Framework. Sustainability, 14(1), 47.*
Article II	***Marquart, H.****, Ueberham, M., & Schlink, U. (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.*
Article III	***Marquart, H.****, Stark, K., & Jarass, J. (2022). How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute. Journal of Transport & Health, 24, 101325.*
Article IV	***Marquart, H.*** *(submitted). Informing about the invisible – Communicating en route air pollution and noise exposure to cyclists and pedestrians using focus groups. Manuscript submitted to Journal of European Transport Research.*

4.1 Article I: Promoting sustainable mobility: To what extent is “health” considered by mobility app studies? A review and a conceptual framework

The following Article I presents a literature review which gives an overview of the state-of-research regarding mobility apps and health topics applied in recent empirical studies. Article I draws on research questions Q1, investigating to what extent and how the ‘health dimension’ – specifically air pollution and noise – is considered in mobility apps applied in mobility research. It is a starting point for investigating if and how information about healthy and pleasant trips can be presented to users, specifically by using mobility apps. The findings of this article provide a background about mobility apps applied in literature and their influence on mobility choices. Moreover, the article provides insights into the strategies used to support more environmentally friendly or healthy mobility.

The article reveals a lack of research applying other health-components in mobility apps, such as air pollution and noise, and gives suggestions for further research. Ultimately, a conceptual framework based on Protection Motivation Theory (see section 2.3) is developed, with the aim to give the topic health more attention in mobility behaviour interventions[27]. Therefore, it serves as a starting point for this thesis and integrates the field of mobility-related information provision with health research. Specifically, this article emphasizes the need to further integrate noise and air pollution information into mobility apps. Article I is well-connected to Article IV (section 4.4), which both frame the thesis by addressing information and communication about healthy and pleasant mobility.

[27] As shown in the theoretical background (section 2.1), this thesis refers to the understanding of practices when referring to people’s *doings*. However, the literature about interventions in mobility choices typically applies the term ‘mobility behaviour’ as part of ‘behavioural change strategies/techniques’, therefore, in Article I the term ‘mobility behaviour’ is frequently used. However, the overall thesis and the other articles of this thesis rather refer to the term ‘practices’ as defined in section 2.1. For more information and discussion on that see section 2.1 or Hargreaves (2011).

Article I

Promoting Sustainable Mobility: To What Extent Is "Health" Considered by Mobility App Studies? A Review and a Conceptual Framework

Heike Marquart [a,b,*] and Julia Schuppan [a]

[a]Institute of Transport Research, German Aerospace Center (DLR) Berlin, 12489 Berlin, Germany

[b]Geography Department, Humboldt University Berlin, 10099 Berlin, Germany

[*]Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

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sustainability

Review

Promoting Sustainable Mobility: To What Extent Is "Health" Considered by Mobility App Studies? A Review and a Conceptual Framework

Heike Marquart [1,2,*] and Julia Schuppan [1]

[1] Institute of Transport Research, German Aerospace Center (DLR) Berlin, 12489 Berlin, Germany; julia.schuppan@dlr.de
[2] Geography Department, Humboldt University Berlin, 10099 Berlin, Germany
* Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

Abstract: Promoting cycling and walking in cities improves individual health and wellbeing and, together with public transport, promotes societal sustainability patterns. Recently, smartphone apps informing and motivating sustainable mobility usage have increased. Current research has applied and investigated these apps; however, none have specifically considered mobility-related health components within mobility apps. The aim of this study is to examine the (potential) role of health-related information provided in mobility apps to influence mobility behavior. Following a systematic literature review of empirical studies applying mobility apps, this paper (1) investigates the studies and mobility apps regarding communicated information, strategies, and effects on mobility behavior and (2) explores how, and to what extent, health and its components are addressed. The reviewed studies focus on environmental information, especially CO_2-emissions. Health is represented by physical activity or calories burned. The self-exposure to air pollution, noise, heat, traffic injuries or green spaces is rarely addressed. We propose a conceptual framework based on protection motivation theory to include health in mobility apps for sustainable mobility behavior change. Addressing people's self-protective motivation could empower mobility app users. It might be a possible trigger for behavior change, leading towards healthy and sustainable mobility and thus, have individual and societal benefits.

Keywords: mobility app; smartphone app; mobility behavior change; health; protection motivation theory; literature review

Citation: Marquart, H.; Schuppan, J. Promoting Sustainable Mobility: To What Extent Is "Health" Considered by Mobility App Studies? A Review and a Conceptual Framework. *Sustainability* **2022**, *14*, 47. https://doi.org/10.3390/su14010047

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1. Introduction

Urban mobility is still strongly relying on motorized transport, causing adverse impacts on people's health and has well known societal impacts such as climate change [1]. Motor vehicle exhausts from motorized transport contain harmful air pollutants, engines cause noise and vehicles require land for infrastructure (e.g., reducing green spaces) [1]. As a result, urban dwellers are exposed to high levels of air pollution and noise, injuries related to traffic crashes, and adverse health impacts due to urban heat islands [2,3]. A lack of urban green spaces and the effects of sedentary mobility cause additional individual health problems in the long-term [2,3]. Even though the concept of healthy cities has been on policy agendas since 1988 and the European Healthy Cities agenda 2014–2018 highly prioritizes transport, many cities still face the aforementioned negative health impacts of increasing urban traffic [2,4,5].

Meanwhile, awareness about healthy lifestyle choices is growing and smartphones are increasingly used to promote (individual) health: monitoring one's health is defined as part of the "quantified-self movement" [6,7]. Health-related smartphone applications help the user self-monitor their behavior and receive feedback on how to improve health, focusing, e.g., on weight loss, diet, physical activity, or illness monitoring [7,8]. "Mhealth" (mobile health technologies) are increasingly used in health research to provide the user with information about their health—including aspects such as air pollution [6]. These technologies have radically increased in recent years and can result in behavior changes towards healthier lifestyles [8,9].

As shown, approaches which digitally inform people about a healthy lifestyle are growing, meanwhile, mobility-related health components receive attention in transport research. However, only recently these two fields are integrated. This study addresses this by analyzing mobility apps applied in recent studies with regard to the addressed informational dimensions, focusing on the mobility-related health dimension and its components [1–3]. We investigate the mobility apps' intervention strategies and discuss the (potential) effects on mobility behavior. We examine the following research question: "To what extent and how is the 'health dimension' (and its components) considered in mobility apps applied in mobility behavior change studies?"

The research comprises three steps:

(1) Reviewing the current state of empirical studies using mobility apps for mobility behavior change and investigating the applied mobility apps regarding their informational dimensions, intervention strategies, and their effect on mobility behavior.
(2) Highlighting the existence and effects of the components of the "health" dimension in mobility apps in empirical research.
(3) Suggesting a theory-based inclusion of "health" components and intervention strategies to support mobility behavior changes through mobility apps.

We intend to examine the interrelation between health and sustainable mobility. For this purpose, we use a systematic literature review that focusses on empirical studies that deal with mobility-related smartphone apps to promote mobility behavior change (i.e., towards sustainable mobility). In Section 2, we provide the theoretical context of the literature review by defining the health concept and locating it in the sustainable mobility discourse and give an overview of mobility behavior change apps. Section 3 presents the methodological approach and the data used. In Section 4 the results of the literature review are presented. Section 5 presents the discussion and introduces a conceptual model to include health in mobility apps. Finally, in Section 6, the conclusion sums up the findings.

2. Background: Defining Health in the Sustainable Mobility Discourse

Recent studies have built conceptual models to define the interrelationship of health and transport, defined by physical activity (including calories burned as part of preventing obesity and prevent cardiovascular diseases), safety and traffic injuries, green space provision, air pollution exposure, noise pollution exposure, extreme weather (e.g., heat), and subjective wellbeing [2,3,10,11]. Concerning the social dimension, transport impacts on health equity, e.g., local pollution of air pollutants or noise, are part of the interrelationship of sustainable transport and health [11].

We argue that addressing these health components can influence people's mobility behavior, their mode/route choices and have co-benefits for sustainability (Figure 1). Following Figure 1, communicating the risks and protective actions regarding each health-component to the individual can address their self-interest in healthy living: If people perceive the severity of a risk and their vulnerability towards one of these health components as high and they feel that they are able to cope with the health risk easily and successfully, they may be motivated to change their behavior towards healthier modes or routes (referring to protection motivation theory (PMT), [12]). As for promoting cycling and walking or public transport, drawing on people's interest in leading a healthier lifestyle may encourage or act as a motivator for using healthy modes of transport or routes with more greenery or less motorized (less polluting) transport. Hence, addressing people's self-interest in health can positively influence sustainability on the societal level.

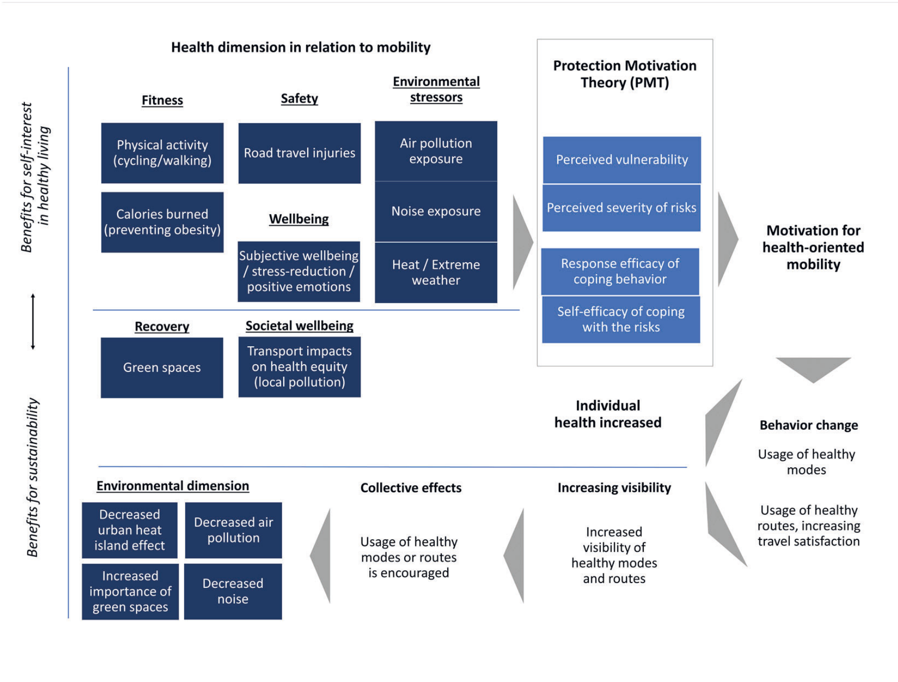

Figure 1. Nexus between mobility behavior and health and its potential to encourage sustainable mobility choices through PMT [12], including important components of transport-related health dimensions. Own illustration, mobility-health components defined by [1–3,10,11], PMT by [12].

For example, knowledge about air pollution can impact cyclists' route choice [13] and the knowledge about available safe cycling routes motivates bicycle usage [14], in turn reducing air and noise pollution. Additionally, increased bicycle usage can enhance the visibility of cyclists as common road users, which may encourage non-cyclists to cycle [15,16]. Not only active mobility promotes physical activity, public transport also has opportunities to improve fitness because people need to walk to the station [10]. Improving wellbeing in public transport by lowering travel time through appropriate travel plans can promote public transport usage [9]. Hence, providing information addressing mobility-health components can have co-benefits in lowering pollution levels, increase importance of greenspaces and a reduction of the heat island effect, i.e., benefits sustainability (Figure 1). Providing information and communication measures, e.g., about health-related factors, can help form intentions to change behavior and support the acceptance of travel demand measures [17].

In this paper we want to examine whether adding health-related information in sustainable mobility communication has the potential to draw on both healthy and sustainable mobility choices and triggers behavior changes. Therefore, we review mobility app studies that intend to change mobility behavior towards sustainable mobility.

The role of mobility apps in supporting route and mode choice has received increased attention in recent years [18]. Mobility apps introduce new possibilities to easily organize one's trip by providing access to information about different modes (shared or public transport), route-characteristics, payment possibilities, real-time trip information (e.g., departure/arrival time, duration), and supplementary information such as CO_2-emitted or kilometers traveled [19]. Thus, they address different informational dimensions [20].

To support sustainable mobility choices, recent studies have increasingly applied smartphone applications to intervene in current mobility behavior. Most studies employ mobility-apps to inform about sustainable trip options or persuade or nudge the user to use sustainable mobility modes through behavioral change strategies, persuasive technologies, or gamification approaches [19,21,22]. Intervention strategies can be education, persuasion, or incentivization (among others) [23]. More specifically, education involves descriptive information and can be achieved through increasing knowledge regarding mobility choices [23]. People are often not aware of the impacts of their mode-choice on the environment and mobility apps with supplementary information can educate [24]. Persuasion is common in mobility behavior change interventions and uses behavior feedback, social influence, comparison or personal suggestions [25]. Giving feedback is supposed to raise awareness about one's (probably undesirable) behavior and activate personal norm/responsibility [26]. Awareness raising is an important step in changing behavior [24]. Moreover, monitoring behavior can be used to compare previous behavior with present behavior and show one's relative performance [27]. As argued in recent literature, the differences in personal characteristics demand personalized information and suggestions [28]. For a comprehensive literature review on persuasive technologies in mobility apps see [25]. Incentivization uses the expectation of rewards as stimulus for behavior change [23] and together with gamification it supports users to achieve their goals [25]. Approaches with monetary incentives often draw on gamification strategies [29]. In competition, users can compare their mobility patterns or goals with others.

Comprehensive reviews regarding the sustainability aspects in mobility app studies were conducted by [30] or [9]. However, there is a gap in the literature concerning whether or to what extent and how the aforementioned mobility related health components (Figure 1) are included in mobility app studies to promote mobility behavior change. This is of concern with regards to the interrelationship and adverse impacts of transport on health and the co-benefits for sustainability. Research is missing which investigates the opportunities of health-related information for sustainable mobility, which appeals to one's self-interest and thus, enhance the possibilities for mobility behavior changes [31]. We draw attention to that applying a systematic literature review as presented in the following.

3. Method: Literature Review

A literature review was conducted focusing on empirical studies that developed or applied a specific mobility app and tested its impact on mobility behavior change. The PRISMA guidelines were used for the literature review [32]. Relevant databases for conference papers and complete articles were searched (Figure 2). Specifically, literature was considered that deals with the effects of mobility-related smartphone applications on mobility behavior change. Following an initial unsystematic paper search to familiarize with the research field, we then used a systematic combination of the following keywords: "behavio* change" AND "mobility" AND "smartphone app*" OR "behavio* change" AND "smartphone" AND "mobility app*". In order to ensure a consistent understanding of mobility as the act of being mobile which recognizes the social and cultural aspects of mobility alongside the mere physical aspects of moving, the focus was placed on literature which used the term "mobility". Therefore, and based on the definition of [33], literature was targeted that acknowledges the needs and abilities of the individual on-the-move and takes the social and psychological questions of being mobile into account. We considered literature on all modes of transport; however, the app should refer to mobility with a destination (e.g., route planning or route tracking for everyday activities) and not mobility as an activity in itself (e.g., cycling/walking for fitness purpose, vacations). To make sure only to include research with apps that have current technological options, the timeframe 2015–2020 was set. However, one article dated before 2015 appeared in our search and was included due to its relevance. The number of retrieved articles was 784. Subsequently, the articles were filtered by screening titles and abstracts were reviewed for eligibility. Only empirical studies were included in which a sample tested/used an existing or developed mobility app and which researched the effects of the mobility app on participants' mobility choices or mobility behavior. Fitness tracking apps or healthcare apps (e.g., hospital patients) were excluded. The reference lists and previous review articles were screened for additional relevant articles. Figure 2 shows the flow diagram of the literature review process based on the PRISMA guidelines [32].

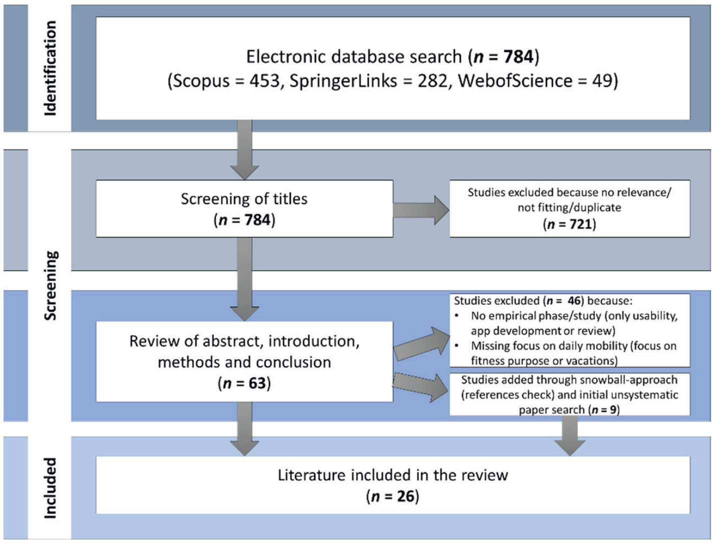

Figure 2. Systematic literature review proceeding according to PRISMA flow diagram [32].

After the literature review process, 26 studies were included in the review. They were analyzed in an inductive-deductive approach: we defined the informational dimensions they could address beforehand (environmental, social, organizational, health). The health specific components were defined based on current literature on the interaction of health and mobility (Figure 1). Moreover, intervention strategies used, and desired effects were based on literature on persuasion strategies in mobility app studies (e.g., [25]) as well as inductively retrieved during the review process. In this study, we specifically draw attention to the informational dimensions of the applied mobility apps.

4. Results

Figure 3 shows the defined four informational dimensions and their specific information given through the mobility apps, which we identified during the review process. The health dimension was subdivided into the health and mobility components derived from the literature (as presented in Figure 1). Ultimately, we investigated the studies regarding their behavior change strategy and effectiveness of the app regarding (intentions of) behavior change, derived from literature and during the review process. Figure 3 displays a summary of the dimensions and app characteristics.

4.1. Overview of the Studies

Table 1 presents an overview of the reviewed empirical studies and the effects of their behavior change interventions. The methods of the empirical studies vary from qualitative to quantitative, having a sample testing/using the respective mobility app. Table 1 represents the results as presented in the studies, describing main findings regarding the effects on mobility behavior change (or intentions) or a possible awareness raising for using more sustainable or healthy modes/routes. A summary of each study is provided in, Appendix A, Table A1.

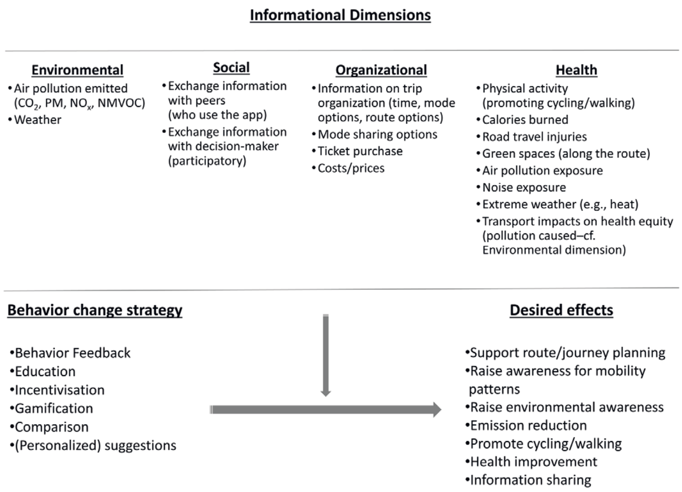

Figure 3. Categories and dimensions for analyzing the literature, defined both deductively based on current literature (mobility-health components [1–3,10,11] and mobility behavior change strategies [9,25]) as well as inductively through the literature review process. Health dimensions defined deductively beforehand for assessment of health dimensions in the apps. Own illustration.

Table 1. Overview of the reviewed studies, the methods applied and their measured effects on mobility behavior.

Study and Name of Mobility App	Method of Empirical Study/Field Trial					Measured Effects of Mobility App (According to the Respective Study) ((Intentions of) Behavior Change; Increased Awareness of Sustainable and Healthy Mobility)
	Qualitative		Quantitative			
	Interview	Focus Group Workshop	Survey/Ques-tionnaire	Assessment of Recorded Routes/Mode	Simulation or Modelling	
[34] OPTIMUM	X		X	X		• Ranking of routes influenced transport choice • Messages raised awareness to change mode/route
[35] PEACOX		X		X		• Positive educational impact that encouraged sustainable travel • Emission information did not produce significant behavior changes (lack of motivation or barriers)
[36] BikeRider		X	X	X	X	• Simulated data shows an increased bike mode share for entire Berlin population and significant decrease for motorized trips (daily purpose)
[37] Cyclers			X	X		• Small monetary rewards (financial incentives) can increase cycling frequency • Gamification does not show an effect on commuting cycling frequency
[38] Move			X	X		• Varying impact of alternative route suggestion incentives on mode choice for different attitudinal profiles
[39] PEACOX		X	X	X		• Increased awareness of unsustainable behavior by providing CO_2 information (especially for car-drivers) • Small and short-term changes in mobility behavior measurable; long-term behavioral change prevented by habits and social conditions

Table 1. *Cont.*

Study and Name of Mobility App	Method of Empirical Study/Field Trial Qualitative		Quantitative			Measured Effects of Mobility App (According to the Respective Study) ((Intentions of) Behavior Change; Increased Awareness of Sustainable and Healthy Mobility)
	Interview	Focus Group Workshop	Survey/Ques-tionnaire	Assessment of Recorded Routes/Mode	Simulation or Modelling	
[27] PEACOX	X	X	X			• Challenges raised awareness and rethink current mobility behavior
[40] Bellidea		X				• Participants felt empowered, sharing knowledge and discussing with local stakeholders • Increased awareness of available possibilities which support mobility behavior change • Increased political and public communication about transport planning
[41] TrafficO2			X	X		• Sample of students (test sample) showed an increase in sustainable preference for their commuting trip from home to university • Monetary rewards are beneficial, but also environmental consciousness is triggering sustainable mobility choices
[42] GoEco!	X		X	X		• Statistically significant impact (decreased CO_2 emissions) in highly car-dependent urban areas for regularly travelled routes • No statistically significant effects in urban areas with high quality public transport
[43] Bewusst-Mobil		X	X	X		• Increased awareness of causes/effects of mode choice related to health or environment • Small changes in mobility behavior • Unintended effects of the game on the use of non-environmentally friendly modes
[44] UbiGo	X	X	X			• Less private car use and increase in public transport, walking and cycling • Development of negative feelings towards private car use, positive feelings towards public transport • Reported changes in mode choice
[29] BetterPoints			X	X		• 79% of every-day car users stated they have reduced their car usage • 89% tracked sustainable/active travel behavior; 47% showed visible long-term behavior changes throughout the project
[45] SUPERHUB		X				• Environmental concerns are not for all users a motivational factor • Personalized behavior change trigger, e.g., personal health • Sharing mobility data accepted when important for sustainable mobility
[46] Love to Ride			X	X		• Gamification campaigns potentially generate ridership or interest in cycling • Small variations of the game incentive have significant effects on a changed mobility behavior
[47] CarbonDiem	X		X	X		• No significant difference in intention to change before/after study • Qualitative interviews show influence on opinions and intentions to change mobility behavior • Identified barriers to change mobility behavior: weather, distance, child drop-offs, cycling safety

Table 1. *Cont.*

Study and Name of Mobility App	Method of Empirical Study/Field Trial					Measured Effects of Mobility App (According to the Respective Study) ((Intentions of) Behavior Change; Increased Awareness of Sustainable and Healthy Mobility)
	Qualitative		Quantitative			
	Interview	Focus Group Workshop	Survey/Ques-tionnaire	Assessment of Recorded Routes/Mode	Simulation or Modelling	
[48] Viagga Roveretgoto				X		• Introducing gamification after 3 weeks lead to a significant shift towards less car use, significant increase in cycling and a moderately significant shift towards bike-sharing
[24] Quantified Traveler			X	X		• Significant decrease in car use and significant increase in walking, small (not significant) increase in train ride • Increasing awareness (environmental, health, financial, time), with the greatest impact on environmental
[49]	X		X			• Walking to near places increased
[26] Blaze			X			• Interventions to induce behavioral change are stage-depended: individuals in early and late stages need different interventions • App induces some progression and prevents regression in some stages of behavioral change • Car use reduces through the stages • App can change proximate implementation intention but not the distal goal/behavioral intentions
[50] Opti-mod'Lyon		X	X			• No influence on mode shift • No effectiveness on daily trip organization due to strong habitual behavior
[51] Metropia				X	X	• Effectiveness of behavioral incentives for peak hour travelers which promote a departure at non-peak hour times • Incentives need to be tailored considering the travel purpose and the time of the day
[52] SMART Mobility			X	X		• Stated preference experiment to choose between usual route and a route with slightly higher travel time that contributes to a certain societal goal led to differences in travelers' compliance behavior • Travelers' compliance with received information significantly depends on the framing of the information, its societal goal and the size of the travel time sacrifice
[53]			X	X		• Survey data showed emotional persuasive strategy of content priming as an effective way to change detour intention and behavior of car users
[54] RideScout (moovel)			X			• Strong shift from driving towards walking and cycling
[55]			X			• Motives for using a mobility app are based on trip efficiency improvement, enjoyment, social interactions and environmentally-friendly travel promotion

4.2. Informational Dimensions and Intervention Strategies of Mobility Apps

The main aim of our review is to investigate the respective informational dimensions the studies address (and their mobility apps comprise), as well as the behavioral change strategies they used. Most apps applied in the studies comprise several informational dimensions, and only some address specific health components, as will be presented in the following (see Table 2 for an overview).

Table 2. Overview of the mobility apps in the reviewed studies (same order as Table 1), categorized according to the informational dimensions they address (E = Environmental, H = Health, S = Social, O = Organizational), specifically covering transport related health components.

Study and Name of Mobility App	Dimension				Transport Related Health Components								
	E	H	S	O	Physical Activity—Actively Promoting Cycling/Walking	Calories Burned	Safety/Road TravelInjuries	Green Spaces along the Route	Air Pollution Exposure	Noise Exposure	Weather (e.g., Heat)	Transport Impact on Health Equity	Well-Being
[34] OPTIMUM	X	X		X	X						X	X	
[35] PEACOX	X	X		X	X						X	X	
[36] BikeRider	X	X			X		X						
[37] Cyclers	X	X	X	X	X		X						
[38] Move	X	X	X	X	X	X						X	
[39] PEACOX	X	X		X	X							X	
[27] PEACOX	X	X		X	X							X	
[40] Bellidea	X	X	X		X							X	
[41] TrafficO2	X	X	X	X	X	X					X	X	
[42] GoEco!	X	X	X		X							X	
[43] BewusstMobil	X	X										X	
[44] UbiGo	X	X		X	X								
[29] BetterPoints	X	X			X	X						X	
[45] SUPERHUB	X	X	X	X		X						X	
[46] Love to Ride	X	X	X		X	X						X	
[47] CarbonDiem	X	X	X		X							X	X
[48] Viagga Roveretgoto	X	X	X	X	X	X						X	
[24] Quantified Traveler	X	X	X	X		X						X	
[49]		X			X	X							
[26] Blaze			X	X									
[50] Optimod'Lyon				X									
[51] Metropia				X									
[52] SMART Mobility	X		X	X	X								
[53]		X		X	X							X	X
[54] RideScout (moovel)				X									
[55]	X	X	X	X	X	X						X	

4.2.1. Environmental Information

The environmental dimension of transport is primarily expressed through the calculation and presentation of emitted CO_2 per mode/route. As already discussed, many mobility apps provide the user with individual baseline mobility patterns including CO_2 emissions [24,38,42]. Other studies monitor and present the CO_2-emissions of different modes through the app [40,47,55]. Most trip planning and trip assessment apps rank alternative routes and modes and highlight their CO_2 emissions. Some even add the user's preferences [34,35,39]. Sustainable/emission-free alternatives, such as bike-sharing services or park and ride solutions, are also included [48]. These studies use the apps to "nudge" the user to both environmentally friendly and personally beneficial mobility choices by ranking the possibilities based on CO_2-emitted and including personal mobility requirements [34] or contribute to congestion reduction in the region [52]. Other apps applied in the studies include personal goals for a behavior change, which are closely linked to environmental topics (e.g., GoEco! with goals such as "reduce CO_2 emissions") [40,42]. These gamification apps also provide users with rewards, such as vouchers or virtual currency, if sustainable modes are used or routes with less CO_2-emissions are chosen [29,36,40–42,44,55]. Some also cooperate with local shops, where the rewards can be exchanged with prices, and support local businesses (e.g., [41]). The app used by [36] also included the possibility to plant real trees in the city of Berlin when obtaining a certain amount of so-called "green credits". Another comparison strategy was sharing the CO_2-emissions saved on social media [55]. Other studies support social interaction through challenging friends with the app to walk more during the week and thus reduce their CO_2-emissions [38].

Mobility pattern changes as a result of environmental feedback have proved successful in the case of systematic routes in car-dependent urban areas [42]. Other studies, however, report only small behavior changes which may be limited to short-term effects, but report increased environmental awareness [39]. Comparing the emitted CO_2 with others proved to be important in 'understanding the numbers' of CO_2-emissions [39]. One study [41] shows that the gamification app, which provides rewards when choosing sustainable modes (incl. CO_2-emissions or calories burned), was effective in increasing sustainable preference for daily commuting trips. Other studies argued that pro-environmental attitudes are not primary incentives for behavioral changes, hence, incentives should rather introduce environmental choices as the "practical choices" rather than the "idealistic" ones [44].

Other negative environmental impacts such as pollutants are rarely included. The authors of [43] developed a gamification app which includes NO_x, NMVOC and PM2.5 emissions alongside CO_2-emissions as highly weighted indicators. The smartphone app in [38] monitors particulate matter (PM) emissions produced.

Weather information was incorporated into three apps. The authors of [39] included information from the publicly accessible weather service in the backend of the app. The authors of [41] added factors to the rewards received per km walking or cycling on rainy days or days with clouds. Further, [34] included weather as a persuading factor to use bike and ride, suggesting a combination of the bicycle with public transport to save CO_2-emission, drawing attention to the "sunny" weather.

4.2.2. Social Information

The social dimension and the influence of peer groups appears to be a very important aspect of mobility apps [24]. Many apps in the reviewed literature include social comparisons. Comparing daily emissions, calories burned, cost, or travel time with different groups such as "the average American", "the average resident of San Francisco" or "other study subjects" was included by [24]. Another study included the possibility to share information recorded by the app on CO_2 emissions saved or calories burned on social media [55]. Additionally, users could give feedback on infrastructure planning and traffic management related to their recorded trips. The study highlights the positive effects of encouraging a dialogue between decision-makers and citizens because it increases the users' perception of having a say in decision-making processes [55]. No other app included participatory approaches similar to that. In the apps studied by [40,42,48], users could compare their performance with other members through gamification such as "level achievements", "weekly leaderboards" or "badges obtained". Further, [41] made it possible to challenge friends in order to increase the virtual currency. Community challenges, in which participants cooperate for increasing their bicycle usage, were applied by [40]. This collective learning, which was the center of the living lab experiment in their study, highly encouraged participants [40]. The authors of [46] explored whether challenges between different teams (e.g., a company against another company) such as riding a bike "for at least 10 min" increased bicycle usage. Challenges between organizations were also included in [29].

One app [47] allows users to view others' experiences of different modes and their written comments (e.g., "feel ready for the day after that walk" [47]). Sharing knowledge was included in another app [45]: users could localize and share sustainable mobility services on a map, compare scores with friends, include mobility related knowledge (e.g., trip plans), and view suggestions from others. Another app also included sharing bicycle route experiences with peers within the app [37]. An app [52] was used to nudge or recommend an alternative "social" route to contribute to congestion alleviation in the region to help others drive faster due to less congestion. The social dimension was often addressed in the reviewed studies and presents good results in supporting mobility behavior changes (Table 1).

4.2.3. Organizational Information

Most apps also address organizational dimensions to support trip planning, especially integrating different modes and sharing options. One app [54] primarily helps users compare transport options with regards to departure and journey time or mode, integrating

MaaS (mobility-as-a-service) approaches such as ride-sourcing, carpooling, or car-, scooter-, and bike-sharing. Real-time multimodal trip organization was also the aim of the app applied by [50]. Cycling route planning and navigation, where users can set preferences, was combined with public transport in [37]. In another app, one could see the possible routes based on different modes of transport, focusing on sustainable modes, and focusing, i.a., on time and economic costs (next to CO_2 emitted and calories burned) [41]. Two apps focusing on organizing car-driver's departure time were tested by [51,53], including information on travel time and current congestion predictions and suggestions how to avoid congestions via alternative routes.

Many apps integrate payment possibilities or give an overview of the prices of different transport modes. The apps studied by [44,55] include the possibility to buy tickets or, in the case of [54], support payment for sharing options and cost comparisons within the app. Additionally, users requested the possibility of comparing the prices of different modes, receive feedback on the costs, and receive information on the prices of alternative mode-choices [44]. This was also integrated into the app by [24]. This app (integrating time, CO_2, and calories alongside costs) lead to significant behavioral shifts towards sustainable travel [24]. The financial dimension was also addressed in a gamification approach by which the trip which saved most money was awarded with scores (in addition to CO_2-emission saved and calories burned) [29]. The organizational dimension mainly comprised multimodal-trip information, costs/tickets and included new mobility services.

4.3. Health Information and Health Components

Many applied mobility apps in the reviewed studies include information about health (Table 2). However, most refer to physical activity by encouraging the user to cycle, which is closely linked to the environmental dimension of decreasing CO_2-emissions. Others provide information on calories burned. The latter is included in the apps in [24,38,47,55] and in two studies with gamification apps [29,41]. The gamification app by [43] also included health benefits from walking and cycling in terms of physical activity as highly weighted indicators to receive rewards. However, they stated that due to already high environment and health knowledge in the area, young people did not increase their knowledge, nor did they make any significant changes to their mobility behavior [43]. In contrast, other gamification apps which included "health points" based on km cycled/walked in a competition achieved an increase in the share of private cycling trips [48]. Encouraging cycling with gamification, i.e., badges obtained, was performed by [37], but did not show effects on cycling frequency. Financial incentives for cycling, however, did motivate bicycle usage [37].

Safety was addressed by two apps [36,37], which pay particular attention to safe and comfortable bicycle routes.

Even though subjective wellbeing is considered a part of health in relation to transport [3], this aspect is rarely addressed. One app [47] included the possibility of entering subjective experiences and ratings of specific modes and trips in the app and provided the possibility to view other user's answers. Hence, the app incorporated aspects of subjective wellbeing. This resulted in a higher consideration of active and sustainable modes as well as in a better understanding of travel experiences of other mode-users [47]. The authors of [53] successfully integrated an emotional persuasion strategy and thus the intrinsic motivation to avoid stress using pictures of upset co-travelers or small children to activate detour behavior.

Recent literature on exposure to air pollution has argued in favor of developing tools which integrate avoiding exposure as an incentive for individual route planning [13]. The inhalation of CO_2, PM or NO_x is reported to have an impact on human health [56,57]. While emitted air pollution of a mode is included in some apps, especially CO_2 (see Section 4.2.1), two apps also included the emission of other traffic-related pollutants (PM, NO_x) [38,43]. However, none include information on personal exposure to or inhalation of air pollution and related health impacts, which could result in behavioral changes regarding departure time or route-choices [13]. Nonetheless, including the produced PM, NO_x or CO_2-emissions in the app, as in many studies (see Section 4.2.1), does address health equity.

Moreover, none of the mobility apps included exposure to noise and only one [39] included aspects regarding extreme weather in route-planning/mode choice, setting the distance of walking or cycling below 15 min during extreme temperatures. The incorporation of green spaces along the route was not addressed by the reviewed apps. Summarizing, we can clearly see that health is addressed in terms of encouraging physical activity, which is also closely linked to the environmental dimension. However, other health related components are missing. We will discuss this lack of health-related information in mobility behavior change apps in Section 5.

5. Discussion

In this paper, we conducted a literature review of recent empirical studies which explore the possibilities of mobility apps to change mobility behavior. We investigated the informational dimensions their applied mobility apps include. Our results provide evidence that certain health aspects, as presented in the introduction, are lacking in mobility apps applied in mobility behavior change research.

5.1. CO_2-Emission Predominant in Studies That Employ Mobility Apps

The results indicate that there is a trend towards including environmental information in mobility apps to support a behavioral change. Environmental information is generally represented as reducing CO_2-emissions. Most research includes the emitted CO_2 of a certain mode/route choice, leading partly to an increase in active modes or public transport, which have great potential to support sustainable mobility (Figure 1). However, other pollutants resulting from traffic, such as NO_x or particulate matter (PM), are rarely included. The emission of CO_2 causes global problems related to climate change and is therefore important to consider for sustainable mobility. However, other traffic-pollutants have severe health impacts on a local level, i.e., affecting health equity. It is argued that these should be considered more [57]. Hence, not only CO_2-emission information should be provided, but also the emission of other pollutants. This could not only support the usage of bicycles, walking or public transport, but also of electric vehicles or micromobility offers (e.g., e-scooters), which rarely cause local pollution. Since the latter are a comparably recent development, few of the reviewed studies have taken them into account.

While the effects of CO_2-emissions are usually perceived as geographically distant, informing citizens about local pollution (NO_x, PM and noise) and mitigation benefits can incentivize environmentally friendly mode usage [58]. Moreover, noise is not included in any of the studies, even though a constant high noise level is among the top environmental health risks in urban areas [59]. The results of the reviewed literature show that environmental concerns may not be a sufficient motivation for mobility behavior change for all users (Table 1) [31]. Some do not want to change their mobility behavior "just for the sake of the environment", thus, additional information may be more convincing [60]. Addressing personal concerns is a possible trigger for behavioral change and applying healthy living interventions in mobility applications would be recommendable [31,60]. CO_2-emissions are the most frequently addressed factor in our reviewed studies, while other pillars of sustainability, such as health or equity, are addressed less. Yet, health is specifically regarded as part of sustainability and the third sustainable development goal (SDG), which explicitly addresses the severity of air pollution among other health-related issues [61]. We argue that there is a need to refine the term sustainability with regards to mobility app studies and incorporate health components more explicitly.

5.2. The Health Dimension and Subjective Wellbeing in Mobility Apps

Urban and transport planning research could further investigate the possibilities that new technologies offer to improve citizens' subjective wellbeing and health in traffic [20]. Generally, providing mobility-information can positively influence subjective wellbeing because it increases the feeling of self-control [62]. However, our literature review shows that mobility apps are lacking which inform about mobility-related health impacts en route and healthier route options. For example, none of the reviewed studies provided the option of searching green spaces or non-polluted (noise and air pollution) routes in their app. As recent research showed, cyclists would be willing to take a less polluted route if it did not add more than about 4 min to their travel time [13]. Other studies also stress the need to communicate information about exposure [63–65], one also using smartphone apps [66]. Studies similar to these are important to understand what impact digitally provided exposure information has on route choices and how that information should be designed. While CO_2-emission feedback addresses the collective dimension, addressing the self-interest of individuals can support sustainable mobility choices as well [60].

After all, communicating personal exposure and health impacts should be considered carefully. As [67] point out, the perception of air pollution and the related health risk can cause negative effects through stress-induced physical reaction and thus cause actual symptoms of sickness. Moreover, information aiming at people's self-interest should not result in an unsustainable outcome at the societal level, e.g., information on pollution levels for open air activities should not result in the usage of private cars, especially as car drivers are not necessarily less exposed to air pollutants than cyclists or pedestrians [68]. Unintended and undesired consequences of mobility behavior interventions have to be considered before intervening in people's daily mobility choice processes [69]. A more holistic view of behavior changes, in which the individuals themselves can change their moral values and not passively follow suggestions from an app, should be considered [52,69]. Strongly pointing out the health benefits of non-motorized transport (e.g., see [68]), additionally incorporating information of the organizational, environmental and social dimension while supporting individual's own decision-making process is crucial. After all, the knowledge of health risks can lead to a change in attitudes and beliefs, and motivate behavior changes [67].

5.3. Limitations of the Reviewed Studies

Many of the reviewed mobility app studies are short-term, have a rather small sample size and are missing evidence that behavioral change lasts (also argued by [45]). Seven of our studies had a field phase which was between 3 months and 1 year, and only two were longer than 6 months. Moreover, the characteristics of the user group have a strong impact on what effect the app has, hence, different user-groups respond to dimensions/arguments in different ways [34,70]. Future research should therefore acknowledge the limitations of the reviewed studies. Researching the impact of mobility apps when incorporating health components would be of interest. Based on the research gap as shown in our findings, we now present our conceptual framework for a mobility app focusing on the health dimension.

5.4. Conceptual Model for Including Health in Mobility Apps

Mobility apps in behavioral change studies mostly address health by means of CO_2-emitted, physical activity, or burned calories. Yet, the latter two do not feature prominently in the apps herein. We argue that health-related information should be given more attention. Improving personal health in addition to enabling contributions to wider global challenges, such as climate change through CO_2-emission reduction, could be an incentive to change mobility behavior [71]. Health should be understood in a broader way in the context of mobility apps: not only physical activity, but also personal exposure (to air and noise pollution, heat), green space provision, or safe routes affect health while traveling in the city [1–3].

As shown in our review, mobility apps including these components, supplementary to persuasion, incentivization, or other informational dimensions, are missing and the effect on mobility behavior changes vary (Tables 1 and 2). Informing about environmental dimensions partly leads to sustainable mobility choices, e.g., people increasingly use active modes or public transport or mobility apps support combinations of cycling, walking and public transport instead of private car usage (Table 1).

However, other studies report rarely any increase in sustainable modes (Table 1). This raises the question whether the altruistic motivation of environmentally friendly mobility is enough or—as we propose—if supplementary information on personal health is needed. As shown in this review, the effects of healthy mobility choices can improve the city's sustainability and urban health situation (Figure 1). We propose a stronger consideration of people's self-interest in protecting themselves from health risks en route and take the protection motivation theory (PMT) [12] as a framework. The PMT is a common theory for explaining health behavior and was even applied for physical activity promotion [72]. According to the PMT, protection motivation is based on four cognitive beliefs, which determine whether a person is motivated and has the intention to protect oneself: (1) threat appraisal (are the current outcomes of a behavior regarded as severe and harmful for oneself) and (2) coping appraisal (is one capable of undertaking protective actions (self-efficacy) and exist possibilities to prevent the risks (response efficacy) [12,72,73]. For promoting healthy and sustainable mobility and increasing physical activity (cycling/walking) or public transport usage, it is important to focus on people's threat appraisal and connect it with coping appraisal. We propose the protection motivation theory (PMT) [12] as a framework for further including health in mobility apps (Figure 4).

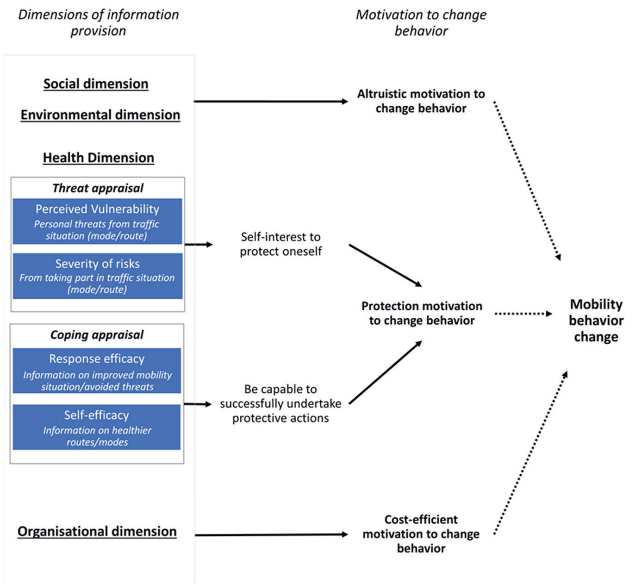

Figure 4. Inclusion of transport and health-related components (taking the protection motivation theory as a framework) to support healthy mobility choices through protection motivation, alongside cost-efficient motivation and altruistic motivation to change behavior. Own illustration, applying the PMT [12].

According to Figure 4, firstly, awareness could be raised for personal vulnerability during daily mobility (defined as threat appraisal) and included in a mobility app by presenting:

- Level of route-specific exposure to harmful air pollutants, noise, or temperatures;
- Traffic injuries on/in specific routes/areas;
- Number of non-active km travelled;
- Percentage of green-space areas on a specific route.

Secondly, the severity of the risks could be communicated by providing general information regarding:

- Health impacts of air pollutants, noise, or temperatures;
- Risk of traffic injuries;
- Risk of obesity/non-active mobility;
- Positive influence of green spaces on health.

Thirdly, providing information on how to protect oneself is part of people's self-efficacy (coping appraisal) and crucial for supporting behavior changes. A mobility app is especially suitable to provide information about:

- Healthier route options (less polluted, greener, safer, cycling/pedestrian friendly (incl. subjective experience (e.g., aesthetics) and wellbeing));
- Healthier mode options (bikeability/walkability, sharing bicycles, intermodal trip planning, i.e., connecting cycling and public transport).

Ultimately, the success of possible mobility behavior changes is of importance (response efficacy) and could be communicated by:

- Avoided pollutants (noise, air pollution), related positive health impacts (e.g., lower blood pressure, less chance of cardiovascular diseases);
- The distance in km travelled close to greenery/water/aesthetic urban form, related positive health impacts (e.g., relaxation, improved wellbeing, lower blood pressure);
- The distance in km cycled/walked, fitness level improved, related positive health impacts (e.g., improved wellbeing, lower blood pressure, higher fitness level).

People's self-interest in protecting oneself combined with healthy alternatives suggested by mobility apps may be a promising method to support healthy mobility behavior, supplementary to other informational dimensions and behavioral change strategies.

However, two aspects should be considered. Firstly, a health-related mobility app should not be overloaded with information, which could lead to difficulties for the user to choose a route or travel mode. It has to be carefully considered which information will be included in a specific app and how it is presented. Exposure-related information should address both threat and coping appraisal. It needs to be relatable/understandable, actionable, relevant to the user, connect with his/her emotions and increase a feeling of collective engagement [74]. Only then it may encourage and sustain fully sustainable (environmentally friendly and healthy) mobility behavior. Consulting a variety of stakeholder with different backgrounds for co-creation is required [74].

Secondly, it has to be considered that the here proposed protection motivation has to compete with other motivations to change behavior, e.g., the cost-efficient motivation (Figure 4). Traditional utility theories argue that travel mode and route choices are based on travel cost, time and effort (among others) [75,76] and longer travel times can decrease travel satisfaction [77]. However, recent studies argue that varying experience factors (e.g., directness, reliability congestion, comfort or even noise, scenery and weather) promote travel activities and influence perceived value of travel time [76]. As for mode choice, non-instrumental factors are also decisive, such as symbolic or affective motives (e.g., for car use) or environmental factors (e.g., weather, land use) and psychological factors (e.g., attitudes, social norms) for cyclists [75,78]. People need to balance the received health information against other decisive factors. Individual's mode or route choice may not follow app-based protection-motivation suggestions straightforward, but when knowing them, they might be considered among other factors.

6. Conclusions

In this paper, we have shown that health components are missing in mobility-related smartphone apps which aim at promoting sustainable mobility. We have investigated which dimensions are addressed and found a strong focus on CO_2-emissions, addressing sustainable mobility in terms of emissions reduction. Incorporating health-related components in mobility communication (e.g., mobility apps) may be just as or even more effective in changing people's mobility behavior towards sustainable and healthy mobility. That could be investigated in future research. Considering the severe impacts of urban mobility on individual health, including health information other than physical activity seems crucial.

It has to be considered that the market for mobility apps is growing and that, as a result, mobility services and possibilities for data generation/provision are changing fast. Nevertheless, our review paper provides new directions for future research agendas. Firstly, we recommend drawing more attention to how people perceive their health, exposure and environment en route and explore how they want to be informed via mobile technologies. Secondly, the effect of providing information on personal exposure, green spaces, or traffic injuries en route needs to be understood to effectively develop information strategies. Especially the effect of giving feedback about personal exposure on behavior is still scarce and needs to receive attention [79]. Exploring the impact of exposure information on mobility behavior through ex-ante and ex-post studies could be beneficial.

Considering that the desired effects on mobility behavior were not always reached in the reviewed studies, the question arises to what extent mobility planning and policy should focus on mobility apps as a suitable measure for sustainable urban mobility. It is important not to lose sight of good urban design, urban governance in planning, and urban dwellers actual needs: mobility apps can be used as a supplement to planning and political strategies, as long as they address the users' needs [80]. Only if healthy and sustainable alternatives exist, i.e., adequate public transport option or cycling/walking infrastructure, a mobility app has the chance to induce sustainable mobility behavior. To understand the user's needs, they have to be actively involved in research and practice regarding information and communication technologies (ICT), such as mobility apps [81]. Mobility apps should empower, inform and enhance the responsibility of urban dwellers to make their own healthy and sustainable mobility decisions, rather than just being passive consumers [69]. The fact that only one of the reviewed apps made successful use of participatory approaches (users sharing experiences with decision-makers) shows the lack of attention that citizen participation receives in mobility apps. Having said that, we finally argue that promoting mobility apps as a tool for sustainable urban governance, healthy urban design, or education could increase awareness for and the actual use of healthy mobility options and healthy routing. The resulting improved wellbeing of urban dwellers may lead to increased satisfaction regarding the institutional planning decisions and is thus desirable for urban policy. With an enhancement of people's environmental health literacy regarding mobility choices, sustainable and healthy mobility can become the center of individual as well as policy-oriented attention.

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Appendix A

Table A1. Overview of the reviewed literature.

Study and Name of Mobility App	Summary of Approach, Aim and Method of the Reviwed Mobility App Studies
[34] OPTIMUM	Approach: User persuadability profiles are developed based on people's mobility behavior and their personality. Personalized interventions, suiting to the persuadability profile of the respective user, are created. Aim: Interventions are part of a route planning app (multimodal route planning) which aims at nudging the user to using sustainable routes. Method: Tested in a pilot study (30 participants, 6 weeks).
[35] PEACOX	Approach: Development and testing of a smartphone-based journey planner, which aims at presenting environmental information for each searched trip to the user ("environmentally themed journey planning app"). Aim: Users reduce their CO_2-emissions and simultaneously receive the required trip information for undertaking their journey. Method: Field trial testing the app in Dublin.
[36] BikeRider	Approach: Users were introduced to new mobility services. Aim: Try to persuade to change their mobility behaviour and leave their comfort zone and behold the impact of these changes via different categories, like traffic system performance and carbon emissions. Method: Gamification approach, with three individual pilot sites, the Berlin STREETLIFE App and the game "BikeRider".
[37] Cyclers	Approach: Try to improve the "Cyclers" smartphone app through evaluating the financial and non-financial motivational features. Aim: To gain a more sustainable and healthier lifestyle, they try to increase regular commuter cycling via the "Cyclers" app in combination with motivational features. Method: Randomized experiment (4 different groups based on different motivational treatments).
[38] Move	Approach: Understand the role of smartphones as mobility behaviour sensors and their ability of various settings profiles to respond to personalized route suggestions incentives offered through smartphones. Aim: Showing user profiles who are likely to accept such incentives and who will more likely choose a more sustainable mode choice. Method: Mobile sensed data collection of real life (n = 3400, 6 months).
[39] PEACOX	Approach: Incorporate persuasive strategies (supported by a choice architecture approach) into a smartphone application (route-planning assistant) for everyday usage. Aim: Providing users with information and solutions while planning a route. Try to influence the user to consider the environmental friendliness of travel modes. Method: Evaluation of the modified route-planning assistant (24 participants, 8 weeks).
[27] PEACOX	Approach: Using the PEACOX system (mobile travel planning application) for analysing the effectiveness and perception of challenges. The challenges are in context of the personal mobility and their influence. Aim: Through which aspects users are willingly participate in these challenges and is there a potential to keep the user interested in using behaviour change support systems. Method: Field study (2 months).
[40] Bellidea	Approach: Exploring information and communication technologies and actively engaging users in co-creating innovative urban services. Aim: To co-create a behaviour change app for reducing car use and in this case reduce car-based traffic. Method: "Living" lab experiment.
[41] TrafficO2	Approach: Investigation of new smartphone and app technology, which promoted a more sustainable choice via mobility modalities. Aim: Change the mobility behaviour while using applications and game rewarding for more sustainable trips. Method: Smartphone app tested by university commuters' group
[42] GoEco!	Approach: Designing and testing a smartphone application named "GoEco!" which contains automatic mobility tracking, eco-feedback, social comparison and gamification elements. Aim: Reducing car use, related CO_2 emissions, energy consumption und enhance/persuade people to make sustainable mobility choices. Method: Randomized controlled trail (one year) in the regions: Cantons Ticino and Zurich (Switzerland).
[43] BewusstMobil	Approach: Concept for a competitive app for students which collects the player's travel data for the game. Aim: Increase environmentally friendly active travel modes during scores and real-life rewards (e.g., shopping vouchers). Method: Iterative process of design, prototyping, and evaluation of the game, three schools in Austria, 57 Students, age 12–18.
[44] UbiGo	Approach: Testing the UbiGo transport broker service and the regarding incentives for users to adopt the new travel services. Aim: Using the service from the UbiGo and obtain a better understanding how to establishing this kind of service. Method: Questionnaires, interviews and travel diaries, 6-month field operational test.
[29] BetterPoints	Approach: Users registered in the app "BetterPoint" obtain different behavioral categories proposed based on engagement etc. for better understanding the data and to tailor future intentions. Aim: Using gamification and rewards for increasing active travel and reduce car journeys. Method: 667 participants, transport project.
[45] SUPERHUB	Approach: Prototyping, testing, and refining of motivational features for environmentally friendly mobility with social influence strategies while using social media. Aim: Behaviour change, better mobility solutions for citizens, guidance for sustainable mobility choice. Method: Three parallel and complementary user studies.
[46] Love to Ride	Approach: Compare different users: smartphone application versus those relies on manual entry. Aim: Users with higher encouragement in digital and/or gamification campaigns are more engaged/have an increased attention. Collecting data can help for urban planning and improve infrastructure. Method: Three large-scale recurring annual encouragement campaigns (66,762 participants).
[47] CarbonDiem	Approach: Using a smartphone application as an intervention tool, the participants must reflect their own and/or others' subjective experiences (SE). Aim: Users should reflect their behavior while using transport modes and make better choices. Method: Automated capturing of data via app and automated reflection, previous self-report study.
[48] Viagga Roveretgoto	Approach: Presenting a service-based gamification framework. This should be an extension to existing services and systems in a smart city. Aim: Behavior change towards sustainable mobility solutions. Method: Testing the gamification framework in the city of Rovereto.

Table A1. *Cont.*

Study and Name of Mobility App	Summary of Approach, Aim and Method of the Reviwed Mobility App Studies
[24] Quantified Traveler	Approach: Presenting a computational travel feedback system using a mobile phone app to gather travel data and give personalized information on carbon, exercise, time and cost footprint to participants. Aim: Learn if participants accept travel data collection, use computed travel information and if this results in attitude or travel behaviour shifts. Method: Travel data collection, questionnaire, 135 participants.
[49]	Approach: Developing an app-based mobility management (MM) which uses step counting and score/ranking functions. Aim: Increase walking and therefor change behavior of the participants. Method: Case study.
[26] Blaze	Approach: Testing Blaze, a mobility behaviour change support system and their influence on travel behaviour. Aim: Obtain a better insight view on the potential role of technology interventions in mobility management and how to achieve behavioural changing in travel. Method: Longitudinal data from a social experiment (over a month).
[50] Optimod'Lyon	Approach: Using Optimod'Lyon (multimodal real-time information navigator for smartphones) and assessing the effects on travel behavior. Aim: User behavior shift from car driving to environment-friendly modes of travel. Method: Quali-quantitative approach, questionnaire, focus groups (50 participants in Lyon).
[51] Metropia	Approach: Analyzing the impact of incentives for main trips and obtain a personal incentive scheme to get an optimal manner at the system wide level. Aim: A behavior shift from peak hour travelling to non-peak hour travelling. Method: Compare two consecutive incentive schemes (1-year), data collected by the Metropia App (2270 users, 364,966 trips, May 2015–May 2018).
[52] SMART Mobility	Approach: Investigate determinants of travelers' compliance with social routing advice. Aim: Obtain a better view on how travel information can be used to obtain system-optimal routes, to obtain a better network efficiency. Method: Stated choice experiment, revealed choice experiment.
[53]	Approach: Applying an emotional persuasive strategy to examine the change of intention and behavior on route decisions. Aim: To keep users from using the Tohoku expressway to use the Joban expressway. Method: Two sets of interventional experiments, track location information (12 days within four weeks), longitudinal online survey.
[54] RideScout (moovel)	Approach: Applying a survey with users of a multi-modal information app to examine the impact of information provision on travel behavior shifts. Aim: Understand how a multi-modal information app may shift travel behaviour. Method: Survey with 130 app users.
[55]	Approach: Investigate motives and use intention for a municipal travel information system. Aim: Understand drivers travel decisions when using the multimodal travel app including type of travel information, integrated services, social and persuasive features. Method: Web-based survey with 822 participants.

References

1. Khreis, H.; May, A.D.; Nieuwenhuijsen, M.J. Health impacts of urban transport policy measures: A guidance note for practice. *J. Transp. Health* **2017**, *6*, 209–227. [CrossRef]
2. Nieuwenhuijsen, M.; Khreis, H. Urban and transport planning, environment and health. In *Integrating Human Health into Urban and Transport Planning: A Framework*; Nieuwenhuijsen, M., Khreis, H., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 3–16.
3. Van Wee, B.; Ettema, D. Travel behaviour and health: A conceptual model and research agenda. *J. Transp. Health* **2016**, *3*, 240–248. [CrossRef]
4. Raustorp, J.; Koglin, T. The potential for active commuting by bicycle and its possible effects on public health. *J. Transp. Health* **2019**, *13*, 72–77. [CrossRef]
5. Tsouros, A.D. Healthy cities: A political movement which empowered local governments to put health and equity high on their agenda. In *Integrating Human Health into Urban and Transport Planning: A Framework*; Nieuwenhuijsen, M., Khreis, H., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 73–88.
6. Larkin, A.; Hystad, P. Towards personal exposures: How technology Is changing air pollution and health research. *Curr. Environ. Health Rep.* **2017**, *4*, 463–471. [CrossRef]
7. Swan, M. Health 2050: The realization of personalized medicine through crowdsourcing, the quantified self, and the participatory biocitizen. *J. Pers. Med.* **2012**, *2*, 93–118. [CrossRef]
8. Hermsen, S.; Frost, J.; Renes, R.J.; Kerkhof, P. Using feedback through digital technology to disrupt and change habitual behavior: A critical review of current literature. *Comput. Hum. Behav.* **2016**, *57*, 61–74. [CrossRef]
9. Sunio, V.; Schmöcker, J.-D. Can we promote sustainable travel behavior through mobile apps? Evaluation and review of evidence. *Int. J. Sustain. Transp.* **2017**, *11*, 553–566. [CrossRef]
10. Mueller, N.; Rojas-Rueda, D.; Basagana, X.; Cirach, M.; Cole-Hunter, T.; Dadvand, P.; Nieuwenhuijsen, M. Urban and transport planning related exposures and mortality: A health impact assessment for cities. *Environ. Health Perspect.* **2017**, *125*, 89–96. [CrossRef]
11. World Health Organization. Health in the Green Economy: Health Co-Benefits of Climate Change Mitigation—Transport Sector. 2012. Available online: https://apps.who.int/iris/handle/10665/70913 (accessed on 3 December 2020).
12. Rogers, R.W. A protection motivation theory of fear appeals and attitude change. *J. Psychol.* **1975**, *91*, 93–114. [CrossRef] [PubMed]
13. Anowar, S.; Eluru, N.; Hatzopoulou, M. Quantifying the value of a clean ride: How far would you bicycle to avoid exposure to traffic-related air pollution? *Transp. Res. Part A Policy Pract.* **2017**, *105*, 66–78. [CrossRef]

14. Hong, J.; Philip McArthur, D.; Stewart, J.L. Can providing safe cycling infrastructure encourage people to cycle more when it rains? The use of crowdsourced cycling data (Strava). *Transp. Res. Part A Policy Pract.* **2020**, *133*, 109–121. [CrossRef]
15. Koglin, T. Organisation does matter—Planning for cycling in Stockholm and Copenhagen. *Transp. Policy* **2015**, *39*, 55–62. [CrossRef]
16. McCarthy, D. 'I'm a normal person': An examination of how utilitarian cyclists in Charleston South Carolina use an insider/outsider framework to make sense of risks. *Urban Stud.* **2010**, *48*, 1439–1455. [CrossRef]
17. Schlag, B.; Schade, J. Public acceptability of traffic demand management in Europe. *Traffic Eng. Control* **2000**, *41*, 314–318.
18. Jamal, S.; Habib, M.A. Smartphone and daily travel: How the use of smartphone applications affect travel decisions. *Sustain. Cities Soc.* **2020**, *53*, 101939. [CrossRef]
19. Gössling, S. ICT and transport behavior: A conceptual review. *Int. J. Sustain. Transp.* **2017**, *12*, 153–164. [CrossRef]
20. Vecchio, G.; Tricarico, L. "May the force move you": Roles and actors of information sharing devices in urban mobility. *Cities* **2019**, *88*, 261–268. [CrossRef]
21. Shaheen, S.; Martin, E.; Cohen, A.; Musunuri, A.; Bhattacharyya, A. *Mobile Apps and Transportation: A Review of Smartphone Apps and A Study of User Response to Multimodal Traveler Information*; Final Report, ITS of UC Berkeley; October University of California at Berkeley, Institute of Transportation Studies: Berkeley, CA, USA, 2016.
22. Fogg, B.J. Persuasive technology: Using computers to change what we think and do. *Ubiquity* **2002**, *2*. [CrossRef]
23. Michie, S.; van Stralen, M.M.; West, R. The behaviour change wheel: A new method for characterising and designing behaviour change interventions. *Implement. Sci.* **2011**, *6*, 42. [CrossRef]
24. Jariyasunant, J.; Abou-Zeid, M.; Carrel, A.; Ekambaram, V.; Gaker, D.; Sengupta, R.; Walker, J.L. Quantified traveler: Travel feedback meets the cloud to change behavior. *J. Intell. Transp. Syst.* **2015**, *19*, 109–124. [CrossRef]
25. Anagnostopoulou, E.; Efthimios, B.; Babis, M.; Johann, S.; Gregoris, M. Persuasive technologies for sustainable mobility: State of the art and emerging trends. *Sustainability* **2018**, *10*, 2128. [CrossRef]
26. Sunio, V.; Schmöcker, J.-D.; Kim, J. Understanding the stages and pathways of travel behavior change induced by technology-based intervention among university students. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *59*, 98–114. [CrossRef]
27. Schrammel, J.; Prost, S.; Mattheiss, E.; Bothos, E.; Tscheligi, M. Using individual and collaborative challenges in behavior change support systems: Findings from a two-month field trial of a trip planner application. In *Persuasive Technology*; Springer International Publishing: Cham, Switzerland, 2015.
28. Anagnostopoulou, E.; Magoutas, B.; Bothos, E.; Schrammel, J.; Orji, R.; Mentzas, G. Exploring the links between persuasion, personality and mobility types in personalized mobility applications. In *Persuasive Technology: Development and Implementation of Personalized Technologies to Change Attitudes and Behaviors*; PERSUASIVE 2017; Lecture Notes in Computer Science; de Vries, P., Oinas-Kukkonen, H., Siemons, L., Beerlage-de Jong, N., van Gemert-Pijnen, L., Eds.; Springer: Cham, Switzerland, 2017; Volume 10171, pp. 107–118. [CrossRef]
29. Bowden, H.; Hellen, G. A data driven, segmentation approach to real world travel behaviour change, using incentives and gamification, in towards user-centric transport in Europe: Challenges, solutions and collaborations. In *Towards User-Centric Transport in Europe*; Müller, B., Meyer, G., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 173–182.
30. Andersson, A.; Winslott Hiselius, L.; Adell, E. Promoting sustainable travel behaviour through the use of smartphone applications: A review and development of a conceptual model. *Travel Behav. Soc.* **2018**, *11*, 52–61. [CrossRef]
31. Chatterton, T.J.; Coulter, A.; Musselwhite, C.; Lyons, G.; Clegg, S. Understanding how transport choices are affected by the environment and health: Views expressed in a study on the use of carbon calculators. *Public Health* **2009**, *123*, e45–e49. [CrossRef]
32. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Group, P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med.* **2009**, *6*, e1000097. [CrossRef]
33. Wilde, M.; Klinger, T. Integrierte Mobilitäts- und Verkehrsforschung: Zwischen Lebenspraxis und Planungstheorie. In *Verkehr und Mobilität zwischen Alltagspraxis und Planungsheorie. Ökologische und soziale Perspektive*; Wilde, M., Gather, M., Neiberger, C., Scheiner, J., Eds.; Springer Fachmedien: Wiesbaden, Germany, 2017; pp. 5–19.
34. Anagnostopoulou, E.; Urbančič, J.; Bothos, E.; Magoutas, B.; Bradesko, L.; Schrammel, J.; Mentzas, G. From mobility patterns to behavioural change: Leveraging travel behaviour and personality profiles to nudge for sustainable transportation. *J. Intell. Inf. Syst.* **2018**, *54*, 157–178. [CrossRef]
35. Brazil, W.; Caulfield, B.; Bothos, E. An Examination of the role of emissions information in transport behaviour: The results of a smart phone trial in Dublin, Ireland. In Proceedings of the 96th Annual Meeting of the Transportation Research Board, Washington, DC, USA, 8–12 January 2017.
36. Kelpin, R.; Giesel, F.; Heinrichs, M. Streetlife field trials—Applied gamification approaches as a key to more sustainable mobility behaviour. In Proceedings of the 44th European Transport Conference, Barcelona, Spain, 5–7 October 2016.
37. Maca, V.; Scasny, M.; Zverinova, I.; Jakob, M.; Hrncir, J. Incentivizing commuter cycling by financial and non-financial rewards. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6033. [CrossRef]
38. Semanjski, I.; Lopez Aguirre, A.J.; De Mol, J.; Gautama, S. Policy 2.0 platform for mobile sensing and incentivized targeted Shifts in mobility behavior. *Sensors* **2016**, *16*, 1035. [CrossRef]
39. Bothos, E.; Prost, S.; Schrammel, J.; Röderer, K.; Mentzas, G. Watch your emissions: Persuasive strategies and choice architecture for sustainable decisions in urban mobility. *PsychNologie J.* **2014**, *12*, 107–126.

40. Cellina, F.; Castri, R.; Simão, J.V.; Granato, P. Co-creating app-based policy measures for mobility behavior change: A trigger for novel governance practices at the urban level. *Sustain. Cities Soc.* **2020**, *53*, 101911. [CrossRef]
41. Di Dio, S.; Massa, F.; Nucara, A.; Peri, G.; Rizzo, G.; Schillaci, D. Pursuing softer urban mobility behaviors through game-based apps. *Heliyon* **2020**, *6*, e03930. [CrossRef]
42. Cellina, F.; Bucher, D.; Mangili, F.; Veiga Simão, J.; Rudel, R.; Raubal, M. A large scale, app-based behaviour change experiment persuading sustainable mobility patterns: Methods, results and lessons learnt. *Sustainability* **2019**, *11*, 2674. [CrossRef]
43. Roider, O.; Wegener, S.; Stark, J.; Judmaier, P.; Michelberger, F.; Barberi, A. Merging virtual world with real-life behavior: A concept for a smartphone app to influence young people's travel behavior. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 241–250. [CrossRef]
44. Sochor, J.; Strömberg, H.; Karlsson, I.C.M. The added value of a new, innovative travel service: Insights from the UbiGo field operational test in Gothenburg, Sweden. In *Internet of Things. IoT Infrastructures*; Springer International Publishing: Cham, Switzerland, 2015.
45. Gabrielli, S.; Maimone, R.; Forbes, P.; Masthoff, J.; Wells, S.; Primerano, L.; Pompa, M. Design challenges in motivating change for sustainable urban mobility. *Comput. Hum. Behav.* **2014**, *41*, 416–423. [CrossRef]
46. Weber, J.; Azad, M.; Riggs, W.; Cherry, C.R. The convergence of smartphone apps, gamification and competition to increase cycling. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *56*, 333–343. [CrossRef]
47. Ross, T.; Burris, A.; Oliveira, L.; Arnott, B.; Araujo-Soares, V. A feasibility study of the effect of phone-based feedback of other commuters' subjective experiences on driver intentions to change. In *Design, User Experience, and Usability: Design Discourse*; Springer International Publishing: Cham, Switzerland, 2015.
48. Kazhamiakin, R.; Marconi, A.; Perillo, M.; Pistore, M.; Valetto, G.; Piras, L.; Perri, N. Using gamification to incentivize sustainable urban mobility. In Proceedings of the IEEE First International Smart Cities Conference (ISC2), Guadalajara, Mexico, 25–28 October 2015.
49. Nakashima, R.; Sato, T.; Maruyama, T. Gamification approach to smartphone-app-based mobility management. *Transp. Res. Procedia* **2017**, *25*, 2344–2355. [CrossRef]
50. Pronello, C.; Veiga-Simão, J.; Rappazzo, V. Can multimodal real-time information systems induce a more sustainable mobility? *Transp. Res. Rec.* **2016**, *2566*, 64–70. [CrossRef]
51. Arian, A.; Ermagun, A.; Zhu, X.; Chiu, Y.-C. An empirical investigation of the reward incentive and trip purposes on departure time behavior change. *Adv. Transp. Policy Plan.* **2018**, *1*, 145–167. [CrossRef]
52. An Essen, M.; Thomas, T.; van Berkum, E.; Chorus, C. Travelers' compliance with social routing advice: Evidence from SP and RP experiments. *Transportation* **2018**, *47*, 1047–1070. [CrossRef]
53. Xu, W.; Kuriki, Y.; Sato, T.; Taya, M.; Ono, C. Does traffic information provided by smartphones increase detour behavior? An examination of emotional persuasive strategy by longitudinal online surveys and location information. In *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 45–57.
54. Shaheen, S.; Cohen, A.; Martin, E. Smartphone app evolution and early understanding from a multimodal app user survey. In *Disrupting Mobility: Impacts of Sharing Economy and Innovative Transportation on Cities*; Meyer, G., Shaheen, S., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 149–164.
55. Dastjerdi, A.M.; Kaplan, S.; de Abreu e Silva, J.; Anker Nielsen, O.; Camara Pereira, F. Use intention of mobility-management travel apps: The role of users goals, technophile attitude and community trust. *Transp. Res. Part A Policy Pract.* **2019**, *126*, 114–135. [CrossRef]
56. Azuma, K.; Kagi, N.; Yanagi, U.; Osawa, H. Effects of low-level inhalation exposure to carbon dioxide in indoor environments: A short review on human health and psychomotor performance. *Environ. Int.* **2018**, *121*, 51–56. [CrossRef] [PubMed]
57. Kelly, F.J.; Fussell, J.C. Air pollution and public health: Emerging hazards and improved understanding of risk. *Environ. Geochem. Health* **2015**, *37*, 631–649. [CrossRef]
58. Mir, H.M.; Behrang, K.; Isaai, M.T.; Nejat, P. The impact of outcome framing and psychological distance of air pollution consequences on transportation mode choice. *Transp. Res. Part D Transp. Environ.* **2016**, *46*, 328–338. [CrossRef]
59. World Health Organization. Environmental Noise Guidlines for the European Region. 2018. Available online: http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2018/environmental-noise-guidelines-for-the-european-region-2018 (accessed on 29 May 2020).
60. Gabrielli, S.; Maimone, R.; Forbes, P.; Masthoff, J.; Wells, S.; Primerano, L.; Pompa, M. Designing motivational features for sustainable urban mobility. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*; ACM: Paris, France, 2013; pp. 1461–1466.
61. UN. Sustainable Development Goal 3; Sustainable Development Goals Knowledge Platform 2019. Available online: https://sustainabledevelopment.un.org/sdg3 (accessed on 29 May 2020).
62. Ben-Elia, E.; Avineri, E. Response to travel information: A behavioural review. *Transp. Rev.* **2015**, *35*, 352–377. [CrossRef]
63. Araban, M.; Tavafian, S.S.; Zarandi, S.M.; Hidarnia, A.R.; Burri, A.; Montazeri, A. A behavioral strategy to minimize air pollution exposure in pregnant women: A randomized controlled trial. *Environ. Health Prev. Med.* **2017**, *22*, 26. [CrossRef]

64. Brody, J.G.; Dunagan, S.C.; Morello-Frosch, R.; Brown, P.; Patton, S.; Rudel, R.A. Reporting individual results for biomonitoring and environmental exposures: Lessons learned from environmental communication case studies. *Environ. Health* **2014**, *13*, 40. [CrossRef] [PubMed]
65. Haddad, H.; de Nazelle, A. The role of personal air pollution sensors and smartphone technology in changing travel behaviour. *J. Transp. Health* **2018**, *11*, 230–243. [CrossRef]
66. Delmas, M.A.; Kohli, A. Can apps make air pollution visible? Learning about health impacts through engagement with air quality information. *J. Bus. Ethics* **2019**, *161*, 279–302. [CrossRef]
67. Orru, K.; Nordin, S.; Harzia, H.; Orru, H. The role of perceived air pollution and health risk perception in health symptoms and disease: A population-based study combined with modelled levels of PM10. *Int. Arch. Occup. Environ. Health* **2018**, *91*, 581–589. [CrossRef]
68. Hartog, J.J.; Boogaard, H.; Nijland, H.; Hoek, G. Do the health benefits of cycling outweigh the risks? *Environ. Health Perspect.* **2010**, *118*, 1109–1116. [CrossRef]
69. Te Brömmelstroet, M. Sometimes you want people to make the right choices for the right reasons: Potential perversity and jeopardy of behavioural change campaigns in the mobility domain. *J. Transp. Geogr.* **2014**, *39*, 141–144. [CrossRef]
70. Haufe, N.; Millonig, A.; Markvica, K. Developing encouragement strategies for active mobility. *Transp. Res. Procedia* **2016**, *19*, 49–57. [CrossRef]
71. Sullivan, R.K.; Marsh, S.; Halvarsson, J.; Holdsworth, M.; Waterlander, W.; Poelman, M.P.; Maddison, R. Smartphone apps for measuring human health and climate change co-benefits: A comparison and quality rating of available apps. *JMIR mHealth uHealth* **2016**, *4*, e135. [CrossRef]
72. Plotnikoff, R.C.; Trinh, L. Protection motivation theory: Is this a worthwhile theory for physical activity promotion? *Exerc. Sport Sci. Rev.* **2010**, *38*, 91–98. [CrossRef]
73. Maddux, J.E.; Rogers, R.W. Protection motivation and self-efficacy: A revised theory of fear appeals and attitude change. *J. Exp. Soc. Psychol.* **1983**, *19*, 469–479. [CrossRef]
74. Riley, R.; de Preux, L.; Capella, P.; Mejia, C.; Kajikawa, Y.; de Nazelle, A. How do we effectively communicate air pollution to change public attitudes and behaviours? A review. *Sustain. Sci.* **2020**, *16*, 2027–2047. [CrossRef]
75. Heinen, E.; van Wee, B.; Maat, K. Commuting by bicycle: An overview of the literature. *Transp. Rev.* **2010**, *30*, 59–96. [CrossRef]
76. Cornet, Y.; Lugano, G.; Georgouli, C.; Milakis, D. Worthwhile travel time: A conceptual framework of the perceived value of enjoyment, productivity and fitness while travelling. *Transp. Rev.* **2021**. [CrossRef]
77. De Vos, J.; Mokhtarian, P.L.; Schwanen, T.; Van Acker, V.; Witlox, F. Travel mode choice and travel satisfaction: Bridging the gap between decision utility and experienced utility. *Transportation* **2016**, *43*, 771–796. [CrossRef]
78. Steg, L. Car use: Lust and must. Instrumental, symbolic and affective motives for car use. *Transp. Res. Part A Policy Pract.* **2005**, *39*, 147–162. [CrossRef]
79. Becker, A.; Marquart, H.; Masson, T.; Helbig, C.; Schlink, U. Impacts of personalized feedback regarding exposure to environmental stressors. *Curr. Pollut. Rep.* 2021, (in press). [CrossRef]
80. Lyons, G. Getting smart about urban mobility—Aligning the paradigms of smart and sustainable. *Transp. Res. Part A Policy Pract.* **2018**, *115*, 4–14. [CrossRef]
81. Lenz, B. Vernetzung—Revolution für die urbane Mobilität der Zukunft? *Elektrotechnik Informationstechnik* **2015**, *132*, 380–383. [CrossRef]

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

The previous Article I has shown that research is lacking which applies mobility apps that include air pollution, noise, subjective experiences or participatory approaches. In the previous Article I it is argued that informing and communicating about these components can be useful for supporting a healthy and pleasant trip.

The following Article II and Article III focus on what factors influence whether cyclists and pedestrians perceive their trip as healthy and pleasant. The aim is to investigate research questions Q2. Article II and III examine how exposure to air pollution, noise and other factors influence perceived health, wellbeing and practices whilst cycling or walking in the city. In order to understand how to communicate air pollution, noise or other health and wellbeing factors, for example with mobility apps (Article I), it is considered necessary to reveal how air pollution and noise are perceived in contrast to actual measured exposure data. Hence, understanding if air pollution and noise exposure information is actually worthwhile to support a perceived healthy and pleasant commute or if other en route factors are more influential. Moreover, it is argued that exposure communication induces protective practices (see Article I and section 2.3), hence, it is of interest to reveal protective practices already undertaken by cyclists and pedestrians. Summarizing, Article II and III identify which factors should be considered in healthy and pleasant trip communication and route planning in the future.

The following Article II draws on research question Q2a, examining how perceived and measured exposure and related practices on-the-move can be investigated using mobile methods (see section 3.3). Hence, in this article a sub-sample of 10 participants is examined (out of the 28 who participated in the go- and ride-alongs). Article II presents mainly the methodological approach, which was developed and applied in this thesis. It will also give first answers to research question Q2b, which is the main focus of the hereafter presented Article III (section 4.3).

Article II

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

Heike Marquart [a,b,*], Maximilian Ueberham[c] and Uwe Schlink[d]

[a]Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany

[b]Geography Department, Humboldt University Berlin, Berlin, Germany

[c]Centre for Environmental Biotechnology, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany

[d]Department of Urban and Environmental Sociology, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany

* Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

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

Heike Marquart [a,b,*], Maximilian Ueberham [c], Uwe Schlink [d]

[a] Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany
[b] Geography Department, Humboldt University Berlin, Berlin, Germany
[c] Centre for Environmental Biotechnology, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany
[d] Department of Urban and Environmental Sociology, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany

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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.

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 and 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 and

* Corresponding author at: Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany.
E-mail addresses: heike.marquart@dlr.de (H. Marquart), maximilian.ueberham@ufz.de (M. Ueberham), uwe.schlink@ufz.de (U. Schlink).

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Hystad, 2017; Schlink and 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 and 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 and 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 and 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 and Urry, 2006). Practiced mobility is experienced through the body, thus, individual's embodied experiences and perceptions should be recognized (Cresswell, 2010; van Duppen and 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 geolocated 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 and 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).

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 and 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

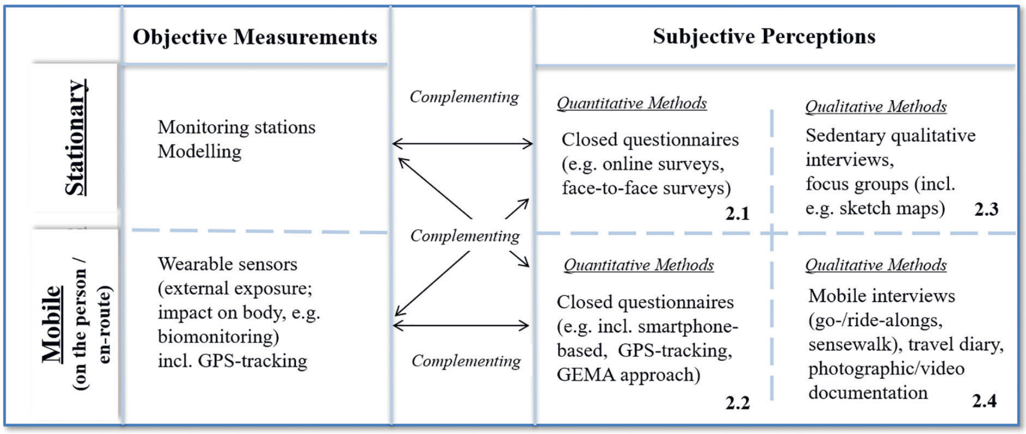

Fig. 1. Overview of different methods for researching the exposure to environmental stressors in the city. The methods can be applied complementary. The numbers relate to the respective chapter.

"revolutionized" personal exposure research (Larkin and 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 and 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 and Walker, 2001). Especially mixed-methods approaches help to research the human-environment relationship, environmental exposure and well-being (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 and 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 and Jones, 2011; Kusenbach, 2003). It is a form of qualitative interview conducted while an interviewer accompanies the interviewee (Carpiano, 2009; King and 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 and Ding, 2008).

Go-/Ride-Along studies investigated participants' relation to place (Hitchings and 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 and Woodroffe, 2017), everyday travel (Hodgson, 2012; Pooley et al., 2013; Pooley et al., 2011; van Duppen and 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 (0.5–2.5 μm) 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 and 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 and 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: 2 s), particle number counts (PNC) from 0.5–2.5 μm, $\#/ft^3$ (interval: 1 min), 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

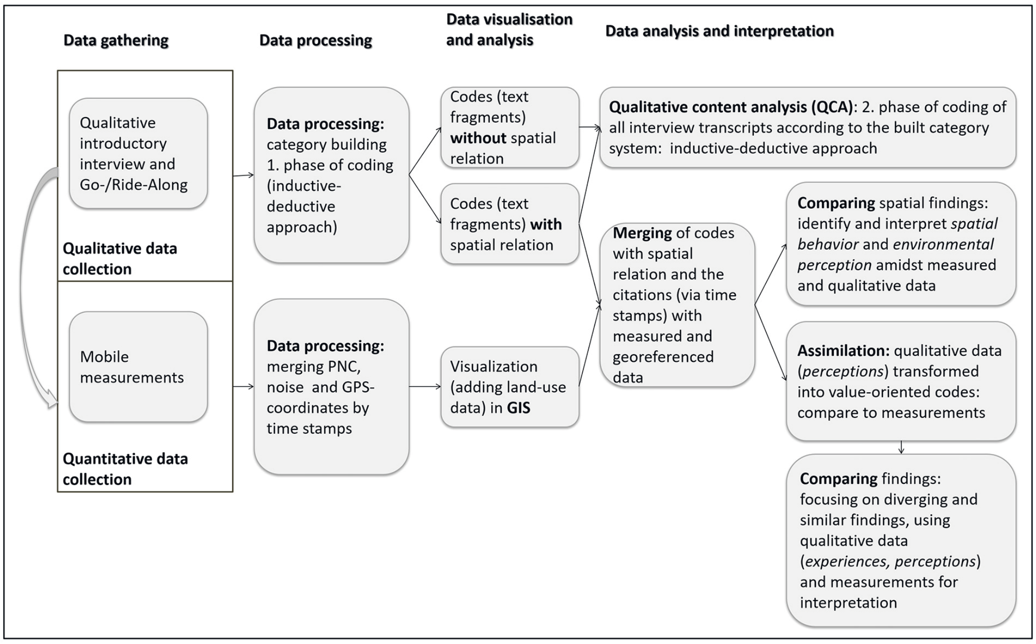

Fig. 2. Research design and data analysis procedure using an integrated mixed-method approach. This article specifically focuses on the data (codes and measured data) with spatial relation.

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 behavior were analysed and complemented by the measurements, supporting an interpretation of the qualitative data.

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 analysed 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. [...] 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 knew that certain route sections help 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

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

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

experience (visual and olfactory) of the interviewee, which is caused by the immediate environmental situation (Fig. 3).

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).

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 and 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 and 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 and 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, behavior and the situational context of people on-the-move (Zhang et al., 2020; Kou et al., 2020). However, they can only capture behavior, 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

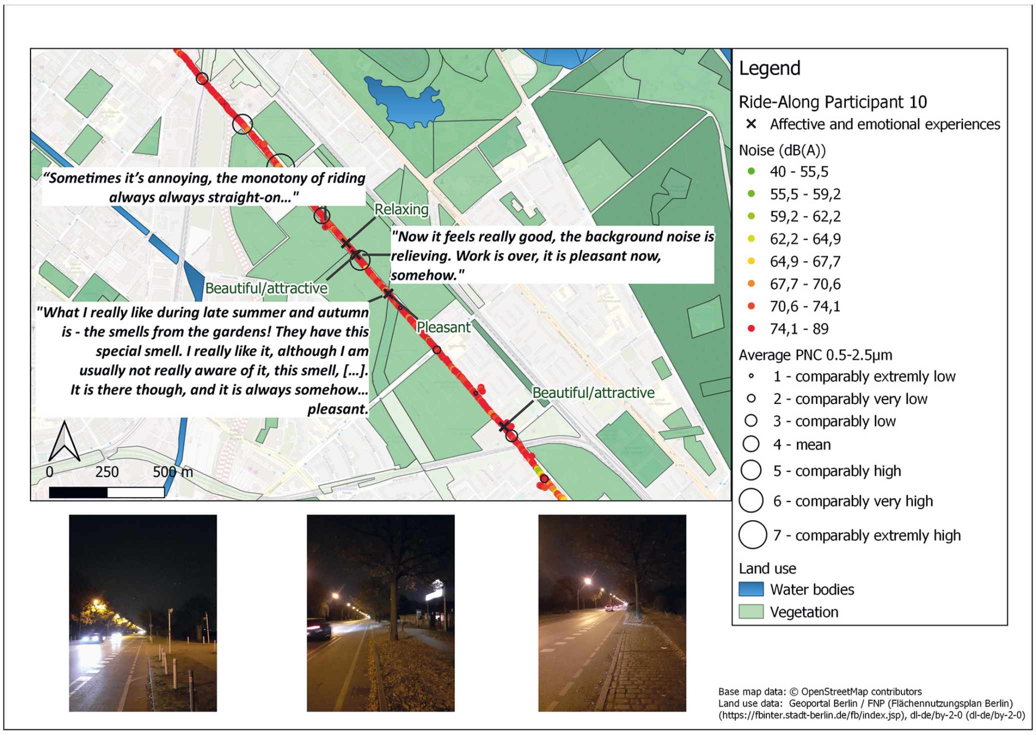

Fig. 3. Ride-Along on an arterial road with high noise pollution and comparably lower air pollution, contrasting the statements of the interviewee who perceives the environment as pleasant and attractive (pictures taken afterwards).

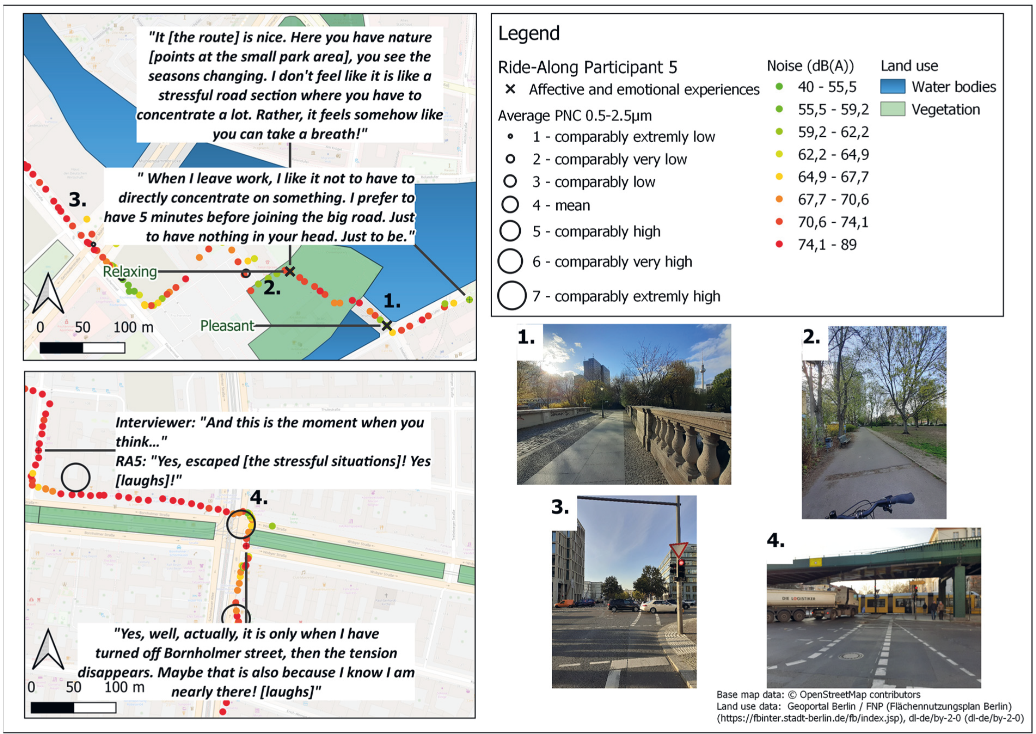

Fig. 4. Example of the importance of contextual information aligning with measured exposure: Greenery and blue space (map above) are evaluated positively, especially in comparison with the "big road" coming ahead. PNC is comparably low. At a main intersection with comparably high PNC and noise levels (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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

situations (Cresswell, 2010; Sheller and Urry, 2006). Our results are in line with van Duppen and Spierings (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 behavior (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 behavior 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 and 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 and 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 and 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 behavior 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 (e.g. being close to home), 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 al., 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. 5). This is important for research, but should also gain more importance in planning decisions.

6. 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 and 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 and 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

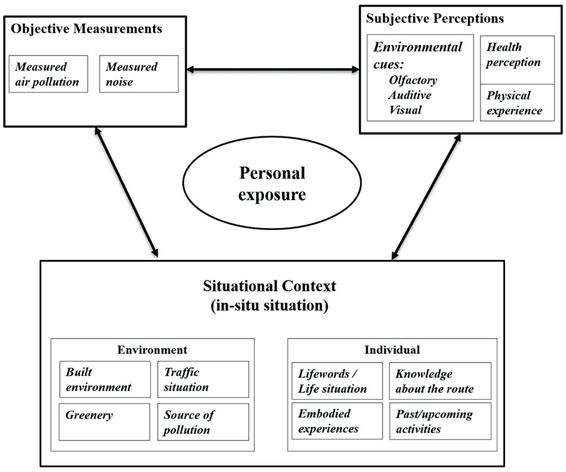

Fig. 5. Extended dimension of personal exposure in traffic: Interlinkages of objective measurements, subjective perceptions and situational context.

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 and 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.

Declarations of interest

None.

Author agreement statement

All authors have seen and approved the final version of the manuscript being submitted. The article is the authors' original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

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Appendix 1. Sample characteristics

Participant #	Mode of transport	Occupation	Age	Gender	Average noise (dB(A))*	Average PNC per dm^3*
RA1	Bicycle (Ride-Along)	Employed	55	f	66,3	3713
RA2	Bicycle (Ride-Along)	Employed	30	m	68,5	11,639
RA3	Bicycle (Ride-Along)	Paternity leave	–	f	63,3	2240
GA4	Walking+subway+bus (Go-Along)	Employed	59	f	65,2	13,118
RA5	Bicycle (Ride-Along)	Employed	42	f	71,6	15,967
GA6	Walking+subway (Go-Along)	Student	32	f	62,7**	18,389
RA7	Bicycle (Ride-Along)	Employed	31	f	68,3**	9454
GA8	Walking+subway (Go-Along)	Student	25	m	63,1**	15,197
RA9	Bicycle (Ride-Along)	Student	24	m	73,1	25,492
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*

References

Alotaibi, R., Bechle, M., Marshall, J.D., Ramani, T., Zietsman, J., Nieuwenhuijsen, M.J., Khreis, H., 2019. Traffic related air pollution and the burden of childhood asthma in the contiguous United States in 2000 and 2010. Environ. Int. 127, 858–867. https://doi.org/10.1016/j.envint.2019.03.041.

Bartels, S., Marki, F., Muller, U., 2015. The influence of acoustical and non-acoustical factors on short-term annoyance due to aircraft noise in the field - the COSMA study. Sci. Total Environ. 538, 834–843. https://doi.org/10.1016/j.scitotenv.2015.08.064.

Bickerstaff, K., Walker, G., 2001. Public understandings of air pollution:the 'localisation' of environmental risk. Glob. Environ. Chang. 11 (2), 133–145. https://doi.org/10.1016/S0959-3780(00)00063-7.

Boettge, B., Hall, D., Crawford, T., 2017. Assessing the bicycle network in St. Louis: a PlaceBased user-centered approach. Sustainability 9 (2), 241. https://doi.org/10.3390/su9020241.

Boschmann, E.E., Cubbon, E., 2014. Sketch maps and qualitative GIS: using cartographies of individual spatial narratives in geographic research. Prof. Geogr. 66 (2), 236–248. https://doi.org/10.1080/00330124.2013.781490.

Büscher, M., 2011. Mobile Methods / ed. by Monika Büscher (1. publ. ed.). Abingdon, Oxon [u.a.]: Routledge.

Camusso, C., Pronello, C., 2016. A study of relationships between traffic noise and annoyance for different urban site typologies. Transp. Res. Part D: Transp. Environ. 44, 122–133. https://doi.org/10.1016/j.trd.2016.02.007.

Carpiano, R.M., 2009. Come take a walk with me: The "Go-Along" interview as a novel method for studying the implications of place for health and well-being. Health Place 15 (1), 263–272. https://doi.org/10.1016/j.healthplace.2008.05.003.

Carreras, H., Ehrnsperger, L., Klemm, O., Paas, B., 2020. Cyclists' exposure to air pollution: in situ evaluation with a cargo bike platform. Environ. Monit. Assess. 192 (7), 470. https://doi.org/10.1007/s10661-020-08443-7.

Chaix, B., 2018. Mobile sensing in environmental health and neighborhood research. Annu. Rev. Public Health 39, 367–384. https://doi.org/10.1146/annurev-publhealth-040617-013731.

Cori, L., Donzelli, G., Gorini, F., Bianchi, F., Curzio, O., 2020. Risk perception of air pollution: a systematic review focused on particulate matter exposure. Int. J. Environ. Res. Public Health 17 (17). https://doi.org/10.3390/ijerph17176424.

Cortesão, J., Brandão Alves, F., Raaphorst, K., 2020. Photographic comparison: a method for qualitative outdoor thermal perception surveys. Int. J. Biometeorol. 64 (2), 173–185. https://doi.org/10.1007/s00484-018-1575-6.

Cresswell, T., 2010. Towards a politics of mobility. Environ. Plan. D. 28 (1), 17–31. https://doi.org/10.1068/d11407.

de Souza, T.B., Alberto, K.C., Barbosa, S.A., 2020. Evaluation of noise pollution related to human perception in a university campus in Brazil. Appl. Acoust. 157, 107023. https://doi.org/10.1016/j.apacoust.2019.107023.

Doherty, S.T., Lemieux, C.J., Canally, C., 2014. Tracking human activity and well-being in natural environments using wearable sensors and experience sampling. Soc. Sci. Med. 106, 83–92. https://doi.org/10.1016/j.socscimed.2014.01.048.

Dons, E., Laeremans, M., Anaya-Boig, E., Avila-Palencia, I., Brand, C., de Nazelle, A., Consortium, P., 2018. Concern over health effects of air pollution is associated to NO 2 in seven european cities. Air Qual. Atmos. Health 11 (5), 591–599. https://doi.org/10.1007/s11869-018-0567-3.

Engström, E., Forsberg, B., 2019. Health impacts of active commuters' exposure to traffic-related air pollution in Stockholm, Sweden. J. Transp. Health 14, 100601. https://doi.org/10.1016/j.jth.2019.100601.

Eriksson, C., Pershagen, G., Nilsson, M., 2018. Biological mechanisms related to cardiovascular and metabolic effects by environmental noise. In: Copenhagen. Retrieved from. http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2018/biologicalmechanisms-related-to-cardiovascular-and-metabolic-effects-by-environmental-noise [accessed: 03.01.2021].

Evans, J., Jones, P., 2011. The walking interview: methodology, mobility and place. Appl. Geogr. *31* (2), 849–858. https://doi.org/10.1016/j.apgeog.2010.09.005.

Finlay, J.M., Bowman, J.A., 2017. Geographies on the move: a practical and theoretical approach to the mobile interview. Prof. Geogr. 69 (2), 263–274. https://doi.org/10.1080/00330124.2016.1229623.

Franck, U., Krüger, M., Schwarz, N., Grossmann, K., Röder, S., Schlink, U., 2013. Heat stress in urban areas: indoor and outdoor temperatures in different urban structure types and subjectively reported well-being during a heat wave in the city of Leipzig. Meteorol. Z. 22 (2), 167–177. https://doi.org/10.1127/0941-2948/2013/0384.

Gany, F., Bari, S., Prasad, L., Leng, J., Lee, T., Thurston, G.D., Zelikoff, J.T., 2017. Perception and reality of particulate matter exposure in New York City taxi drivers. J. Expo. Sci. Environ. Epidemiol. 27 (2), 221–226. https://doi.org/10.1038/jes.2016.23.

Garcia, C.M., Eisenberg, M.E., Frerich, E.A., Lechner, K.E., Lust, K., 2012. Conducting go-along interviews to understand context and promote health. Qual. Health Res. 22 (10), 1395–1403. https://doi.org/10.1177/1049732312452936.

Gössling, S., Humpe, A., Litman, T., Metzler, D., 2019. Effects of perceived traffic risks, noise, and exhaust smells on bicyclist behaviour: an economic evaluation. Sustainability 11 (2), 408. https://doi.org/10.3390/su11020408.

Haddad, H., de Nazelle, A., 2018. The role of personal air pollution sensors and smartphone technology in changing travel behaviour. J. Transp. Health. https://doi.org/10.1016/j.jth.2018.08.001.

Hänninen, O., et al., 2014. Environmental burden of disease in Europe: assessing nine risk factors in six countries. Environ. Health Perspect. 122 (5), 439–446. https://doi.org/10.1289/ehp.1206154.

Hein, J.R., Evans, J., Jones, P., 2008. Mobile methodologies: theory, technology and practice. Geogr. Compass 2 (5), 1266–1285. https://doi.org/10.1111/j.1749-8198.2008.00139.x.

Hitchings, R., Jones, V., 2004. Living with plants and the exploration of botanical encounter within human geographic research practice. Ethics Place Environ. 7 (1–2), 3–18. https://doi.org/10.1080/1366879042000264741.

Hodgson, F., 2012. Everyday connectivity: equity, technologies, competencies and walking. J. Transp. Geogr. 21, 17–23. https://doi.org/10.1016/j.jtrangeo.2011.11.001.

Howell, N.A., Tu, J.V., Moineddin, R., Chen, H., Chu, A., Hystad, P., Booth, G.L., 2019. Interaction between neighborhood walkability and traffic-related air pollution on hypertension and diabetes: the CANHEART cohort. Environ. Int. 132, 104799. https://doi.org/10.1016/j.envint.2019.04.070.

Jensen, S.U., 2007. Pedestrian and bicyclist level of service on roadway segments. Transp. Res. Rec. 2031 (1), 43–51. https://doi.org/10.3141/2031-06.

Johnson, B.B., 2012. Experience with urban air pollution in Paterson, New Jersey and implications for air pollution communication. Risk Anal. 32 (1), 39–53. https://doi.org/10.1111/j.1539-6924.2011.01669.x.

Kabisch, N., Püffel, C., Masztalerz, O., Hemmerling, J., Kraemer, R., 2021. Physiological and psychological effects of visits to different urban green and street environments in older people: a field experiment in a dense inner-city area. Landsc. Urban Plan. 207 https://doi.org/10.1016/j.landurbplan.2020.103998.

Kelly, F.J., Fussell, J.C., 2015. Air pollution and public health: emerging hazards and improved understanding of risk. Environ. Geochem. Health 37 (4), 631–649. https://doi.org/10.1007/s10653-015-9720-1.

Kelly, C.E., Tight, M.R., Hodgson, F.C., Page, M.W., 2011. A comparison of three methods for assessing the walkability of the pedestrian environment. J. Transp. Geogr. 19 (6), 1500–1508. https://doi.org/10.1016/j.jtrangeo.2010.08.001.

Kestens, Y., Wasfi, R., Naud, A., Chaix, B., 2017. "Contextualizing context": reconciling environmental exposures, social networks, and location preferences in health research. Curr. Environ. Health Rep. 4 (1), 51–60. https://doi.org/10.1007/s40572-017-0121-8.

King, K.E., 2015. Chicago residents' perceptions of air quality: objective pollution, the built environment, and neighborhood stigma theory. Popul. Environ. 37 (1), 1–21. https://doi.org/10.1007/s11111-014-0228-x.

King, A.C., Woodroffe, J., 2017. Walking interviews. In: Liamputtong, P. (Ed.), Handbook of Research Methods in Health Social Sciences. Springer Singapore, Singapore, pp. 1–22.

Klettner, S., Huang, H., Schmidt, M., Gartner, G., 2013. Crowdsourcing affective responses to space. J. Cartogr. Geogr. Inform. 63, 66–73. https://doi.org/10.1007/BF03546096.

Kou, L., Tao, Y., Kwan, M.-P., Chai, Y., 2020. Understanding the relationships among individual-based momentary measured noise, perceived noise, and psychological stress: a geographic ecological momentary assessment (GEMA) approach. Health Place 64, 102285. https://doi.org/10.1016/j.healthplace.2020.102285.

Kowalewski, M., Bartłomiejski, R., 2020. Is it research or just walking? Framing walking research methods as "non-scientific". Geoforum *114*, 59–65. https://doi.org/10.1016/j.geoforum.2020.06.002.

Kuckartz, U., 2014. Mixed Methods Methodologie, Forschungsdesigns und Analyseverfahren / von Udo Kuckartz. Springer VS, Wiesbaden.

Künzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Sommer, H., 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. Lancet 356 (9232), 795–801. https://doi.org/10.1016/s0140-6736(00)02653-2.

Kusenbach, M., 2003. Street phenomenology: the go-along as ethnographic research tool. Ethnography 4 (3), 455–485. https://doi.org/10.1177/146613810343007.

Kwan, M.-P., Ding, G., 2008. Geo-narrative: extending geographic information systems for narrative analysis in qualitative and mixed-method research. Prof. Geogr. 60 (4), 443–465. https://doi.org/10.1080/00330120802211752.

Larkin, A., Hystad, P., 2017. Towards personal exposures: how technology is changing air pollution and health research. Curr. Environ. Health Rep. 4 (4), 463–471. https://doi.org/10.1007/s40572-017-0163-y.

Latour, B., 2005. Reassembling the Social an Introduction to Actor-Network-Theory / Bruno Latour. Oxford University Press, New York.

Leaffer, D., Wolfe, C., Doroff, S., Gute, D., Wang, G., Ryan, P., 2019. Wearable ultrafine particle and noise monitoring sensors jointly measure personal co-exposures in a pediatric population. Int. J. Environ. Res. Public Health 16 (3). https://doi.org/10.3390/ijerph16030308.

Lenzholzer, S., Klemm, W., Vasilikou, C., 2018. Qualitative methods to explore thermo-spatial perception in outdoor urban spaces. Urban Clim. 23, 231–249. https://doi.org/10.1016/j.uclim.2016.10.003.

Li, F., Zhou, T., 2020. Effects of objective and subjective environmental pollution on well-being in urban China: a structural equation model approach. Soc. Sci. Med. 249 (1982), 112859. https://doi.org/10.1016/j.socscimed.2020.112859.

Li, Y., Guan, D., Tao, S., Wang, X., He, K., 2018. A review of air pollution impact on subjective well-being: survey versus visual psychophysics. J. Clean. Prod. 184, 959–968. https://doi.org/10.1016/j.jclepro.2018.02.296.

Lin, W.-H., Pan, W.-C., Yi, C.-C., 2019. "Happiness in the air?" the effects of air pollution on adolescent happiness. BMC Public Health 19 (1), 795. https://doi.org/10.1186/s12889-019-7119-0.

Ma, J., Tao, Y., Kwan, M.-P., Chai, Y., 2020. Assessing mobility-based real-time air pollution exposure in space and time using smart sensors and GPS trajectories in Beijing. Ann. Am. Assoc. Geograph. 110 (2), 434–448. https://doi.org/10.1080/24694452.2019.1653752.

Marquart, H., Schlink, U., Ueberham, M., 2020. The planned and the perceived city: A comparison of cyclists' and decision-makers' views on cycling quality. J. Transp. Geogr. *82*, 102602. https://doi.org/10.1016/j.jtrangeo.2019.102602.

Marquart, H., Schlink, U., Nagendra, S.M., Shiva, 2021. Complementing mobile measurements with Walking Interviews: a case study on personal exposure of commuters in Chennai, India. Int. J. Urban Sci. 1–14. https://doi.org/10.1080/12265934.2020.1871060.

Martens, A.L., Reedijk, M., Smid, T., Huss, A., Timmermans, D., Strak, M., Vermeulen, R.C.H., 2018. Modeled and perceived RF-EMF, noise and air pollution and symptoms in a population cohort. Is perception key in predicting symptoms? Sci. Total Environ. 639, 75–83. https://doi.org/10.1016/j.scitotenv.2018.05.007.

McNabola, A., Broderick, B.M., Gill, L.W., 2008. Relative exposure to fine particulate matter and VOCs between transport microenvironments in Dublin: personal exposure and uptake. Atmos. Environ. 42 (26), 6496–6512. https://doi.org/10.1016/j.atmosenv.2008.04.015.

Mila, C., Salmon, M., Sanchez, M., Ambros, A., Bhogadi, S., Sreekanth, V., Tonne, C., 2018. When, where, and what? Characterizing personal PM2.5 exposure in periurban India by integrating GPS, wearable camera, and ambient and personal monitoring data. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b03075.

Modig, L., Forsberg, B., 2007. Perceived Annoyance and Asthmatic Symptoms in Relation to Vehicle Exhaust Levels Outside Home: A Cross-Sectional Study. A Global Access Science Source, Environmental Health, p. 6. https://doi.org/10.1186/1476-069X-6-29.

Nieuwenhuijsen, M.J., 2016. Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. Environ. Health 15 (Suppl. 1), 38. https://doi.org/10.1186/s12940-016-0108-1.

Nikolopoulou, M., Kleissl, J., Linden, P.F., Lykoudis, S., 2011. Pedestrians' perception of environmental stimuli through field surveys: focus on particulate pollution. Sci. Total Environ. 409 (13), 2493–2502. https://doi.org/10.1016/j.scitotenv.2011.02.002.

Okokon, E.O., Yli-Tuomi, T., Turunen, A.W., Taimisto, P., Pennanen, A., Vouitsis, I., Lanki, T., 2017. Particulates and noise exposure during bicycle, bus and car commuting: a study in three European cities. Environ. Res. 154, 181–189. https://doi.org/10.1016/j.envres.2016.12.012.

Orru, K., Nordin, S., Harzia, H., Orru, H., 2018. The role of perceived air pollution and health risk perception in health symptoms and disease: a population-based study combined with modelled levels of PM10. Int. Arch. Occup. Environ. Health 91 (5), 581–589. https://doi.org/10.1007/s00420-018-1303-x.

Pooley, C.G., Horton, D., Scheldeman, G., Tight, M., Jones, T., Chisholm, A., Jopson, A., 2011. Household decision-making for everyday travel: a case study of walking and cycling in Lancaster (UK). J. Transp. Geogr. 19 (6), 1601–1607. https://doi.org/10.1016/j.jtrangeo.2011.03.010.

Pooley, C.G., Horton, D., Scheldeman, G., Mullen, C., Jones, T., Tight, M., Chisholm, A., 2013. Policies for promoting walking and cycling in England: a view from the street. Transp. Policy 27, 66–72. https://doi.org/10.1016/j.tranpol.2013.01.003.

Przyborski, A., Wohlrab-Sahr, M., 2014. Qualitative Sozialforschung : ein Arbeitsbuch / von Aglaja Przyborski und Monika Wohlrab-Sahr, 4. ed. Oldenbourg, München.

Reames, T.G., Bravo, M.A., 2019. People, place and pollution: investigating relationships between air quality perceptions, health concerns, exposure, and individual- and area-level characteristics. Environ. Int. 122, 244–255. https://doi.org/10.1016/j.envint.2018.11.013.

Sagl, G., Resch, B., Blaschke, T., 2015. Contextual sensing: integrating contextual information with human and technical geo-sensor information for smart cities. Sensors (Basel) 15 (7), 17013–17035. https://doi.org/10.3390/s150717013.

Sass, V., Kravitz-Wirtz, N., Karceski, S.M., Hajat, A., Crowder, K., Takeuchi, D., 2017. The effects of air pollution on individual psychological distress. Health Place 48, 72–79. https://doi.org/10.1016/j.healthplace.2017.09.006.

Schlink, U., Ueberham, M., 2020. Perspectives of individual-worn sensors assessing personal environmental exposure. Engineering. https://doi.org/10.1016/j.eng.2020.07.023.

Sears, C.G., Braun, J.M., Ryan, P.H., Xu, Y., Werner, E.F., Lanphear, B.P., Wellenius, G.A., 2018. The association of traffic-related air and noise pollution with maternal blood pressure and hypertensive disorders of pregnancy in the HOME study cohort. Environ. Int. 121, 574–581. https://doi.org/10.1016/j.envint.2018.09.049.

Sharp, G., Denney, J.T., Kimbro, R.T., 2015. Multiple contexts of exposure: activity spaces, residential neighborhoods, and self-rated health. Soc. Sci. Med. 146, 204–213. https://doi.org/10.1016/j.socscimed.2015.10.040.

Sheller, M., Urry, J., 2006. The new mobilities paradigm. Environ. Plan. A. 38 (2), 207–226. https://doi.org/10.1068/a37268.

Snyder, E.G., Watkins, T.H., Solomon, P.A., Thoma, E.D., Williams, R.W., Hagler, G.S.W., Preuss, P.W., 2013. The changing paradigm of air pollution monitoring. Environ. Sci. Technol. 47 (20), 11369–11377. https://doi.org/10.1021/es4022602.

Spinney, J., 2016. A place of sense: a kinaesthetic ethnography of cyclists on mont ventoux. Environ. Plan. D. 24 (5), 709–732. https://doi.org/10.1068/d66j.

Stallen, P.J., 1999. A theoretical framework for environmental noise annoyance. Noise Health 1 (3), 69–79.

Stefansdottir, H., 2014. Urban routes and commuting bicyclist's aesthetic experience. FORMakademisk 7. https://doi.org/10.7577/formakademisk.777.

Steinle, S., Reis, S., Sabel, C.E., 2013. Quantifying human exposure to air pollution—moving from static monitoring to spatio-temporally resolved personal exposure assessment. Sci. Total Environ. 443, 184–193. https://doi.org/10.1016/j.scitotenv.2012.10.098.

Steinmetz-Wood, M., Pluye, P., Ross, N.A., 2019. The planning and reporting of mixed methods studies on the built environment and health. Prev. Med. 126, 105752. https://doi.org/10.1016/j.ypmed.2019.105752.

Szeremeta, B., Zannin, P.H.T., 2009. Analysis and evaluation of soundscapes in public parks through interviews and measurement of noise. Sci. Total Environ. 407 (24), 6143–6149. https://doi.org/10.1016/j.scitotenv.2009.08.039.

Ueberham, M., Schlink, U., 2018. Wearable sensors for multifactorial personal exposure measurements – a ranking study. Environ. Int. 121, 130–138. https://doi.org/10.1016/j.envint.2018.08.057.

Ueberham, M., Schmidt, F., Schlink, U., 2018. Advanced smartphone-based sensing with open-source task automation. Sensors (Basel, Switzerland) 18 (8), 2456. https://doi.org/10.3390/s18082456.

Ueberham, M., Schlink, U., Dijst, M., Weiland, U., 2019. Cyclists' multiple environmental urban exposures—comparing subjective and objective measurements. Sustainability 11 (5). https://doi.org/10.3390/su11051412.

van Duppen, J., Spierings, B., 2013. Retracing trajectories: the embodied experience of cycling, urban sensescapes and the commute between 'neighbourhood' and 'city' in Utrecht, NL. J. Transp. Geogr. 30, 234–243. https://doi.org/10.1016/j.jtrangeo.2013.02.006.

Verbeek, T., 2018. The relation between objective and subjective exposure to traffic noise around two suburban highway viaducts in Ghent: lessons for urban environmental policy. Local Environ. 23 (4), 448–467. https://doi.org/10.1080/13549839.2018.1428791.

von Szombathely, M., Albrecht, M., Augustin, J., Bechtel, B., Dwinger, I., Gaffron, P., Strüver, A., 2018. Relation between observed and perceived traffic noise and socio-economic status in urban blocks of different characteristics. Urban Sci. 2 (1), 20. https://doi.org/10.3390/urbansci2010020.

WHO, 2018. Environmental Noise Guidlines for the European Region, 9789289053563. World Health Organization. Retrieved from. http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2018/environmental-noise-guidelines-for-the-european-region-2018 [accessed: 03.01.2021].

Zeile, P., Resch, B., Loidl, M., Petutschnig, A., Dörrzapf, L., 2016. Urban emotions and cycling experience – enriching traffic planning for cyclists with human sensor data. GI_Forum 1, 204–216. https://doi.org/10.1553/giscience2016_01_s204.

Zhang, X., Zhou, S., Kwan, M.-P., Su, L., Lu, J., 2020. Geographic ecological momentary assessment (GEMA) of environmental noise annoyance: the influence of activity context and the daily acoustic environment. Int. J. Health Geogr. 19, 50. https://doi.org/10.1186/s12942-020-00246-w.

4.3 Article III: How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute

The previous Article II has presented and discussed the go- and ride-alongs complemented by wearable sensors and gave first findings regarding the importance of the situational context. The following Article III will go deeper into the situational context, the sensory awareness, perceptions and practices on-the-move. It will examine if perceived and measured air pollution and noise are in line and if not, what other factors are decisive for a perceived healthy and pleasant commute (research question Q2b).

The findings from all go- and ride-alongs complemented by wearable sensors, in total of 28 participants, will be presented and discussed. Specifically, their sensory awareness will be investigated (for more information on sensory awareness see section 2). Therefore, their perceived air and smells, their perceived sounds and their visual experiences will be explored. A focus will be on perceived air pollution and noise, contrasted to measurable air pollution and noise of the immediate situation. Moreover, protective practices en route will be discovered and related to the external environment. Ultimately, Article III will identify which en route factors are important for making cycling and walking in cities attractive and present which factors impact cyclists and pedestrians perceived health and wellbeing on-the-move.

Article II and III provide a comprehensive understanding of cyclists and pedestrians daily commute. They serve as a basis for discussing and developing information and communication technologies which can inform about a healthy *and* pleasant commute. These are further discussed in the hereafter presented Article IV.

Article III

How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute

Heike Marquart[a b *], Kerstin Stark[a] and Julia Jarass[a]

[a] Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany

[b] Geography Department, Humboldt University Berlin, Berlin, Germany

* Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

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How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute

Heike Marquart [a,b,*], Kerstin Stark [a], Julia Jarass [a]

[a] Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany
[b] Geography Department, Humboldt University Berlin, Berlin, Germany

A R T I C L E I N F O

Keywords:
Ride-along
Go-along
Sensory awareness
Perception
Air pollution
Noise

A B S T R A C T

Background: Commuting by bicycle or on foot is beneficial for health and wellbeing. However, cycling and walking alongside road traffic poses the risk of air pollution and noise exposure. Traditionally, exposure research is based on objective measurements. Only recently have subjective perceptions gained attention. The perceived exposure to air pollution and noise en route and the momentary sensory awareness in traffic has rarely been investigated. This study addresses this research gap. The aim was to examine cyclists'/pedestrians' sensory awareness, perceived and measured exposure, and practices to reduce health risks and improve wellbeing en route.
Methods: A mixed-methods approach was applied: (1) go-/ride-alongs with 28 participants in Berlin, Germany, were conducted. Cyclists/pedestrians were accompanied on their commute home from work. Meanwhile, a semi-structured qualitative interview during cycling/walking was applied to discover experiences, practices and perceptions on-site. (2) Simultaneously, noise (dB (A)), GPS and air pollution (particulate matter) were registered with wearable sensors.
Results: Measured exposure was partly in line with perceived exposure. However, some situations with high exposure were evaluated as positive due to sensory awareness (greenery/water, urban aesthetics) or social cues (other people, neighborhood areas). Community feelings, aesthetic/interesting urban form and passing people who perform leisure activities and, thus, take ownership of their city, improved a pleasant commute. Using hidden paths to include greenery and protective practices (e.g., increasing the distance from emitters) were examined.
Conclusions: Cyclists and pedestrians are directly exposed to their environment, which jointly influences health and wellbeing. Air pollution and noise need to be addressed, as do exposure perceptions and other sensory experiences. Passing community areas, having an interesting trip, seeing/smelling blue and green spaces, and the quietness associated with these experiences improve a cyclist's/pedestrian's wellbeing during their commute. Further research on how to plan for and communicate about healthy and pleasant routes is needed.

1. Introduction

Urban transport plays a key role in improving health and wellbeing in cities (Nieuwenhuijsen and Khreis, 2019). Motorized

* Corresponding author. Institute of Transport Research German Aerospace Center (DLR), 12489, Berlin, Germany.
E-mail address: heike.marquart@dlr.de (H. Marquart).

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transport is responsible for harmful air pollutants and high noise levels, which adversely impact urban dwellers' physical and mental health (Li et al., 2018; Nieuwenhuijsen, 2016; WHO, 2018). In European cities, traffic noise and airborne particulate matter are two of the leading environmental health risk factors and are especially high alongside high-density road traffic (Okokon et al., 2017; Hänninen et al., 2014). Next to physical health impacts, wellbeing is highly related to transport and is influenced during the travel itself or in the long-term (Chatterjee et al., 2020; Nordbakke and Schwanen, 2013; Reardon and Abdallah, 2013).

In particular, cyclists and pedestrians face high levels of air pollution and noise alongside road traffic (Apparicio et al., 2016; Chaney et al., 2017). Then again, active mobility promotes physical and mental health, increases wellbeing and the overall satisfaction of travel (Chatterjee et al., 2020; Mouratidis et al., 2019; Mytton et al., 2016; Synek and Koenigstorfer, 2019). To enhance active mobility, it is, therefore, important to improve cyclists'/pedestrians' experience during travel and minimize their exposure, leading to improved wellbeing and health.

Research on air pollution or noise exposure during travel and its relation to travel behavior, and its social and health impacts are still limited (Poom et al., 2021). Most exposure studies see exposure as being stable over space and time (stationarity bias) and refer to measured exposure and its physical health impacts, whereas research on the perceived exposure from a nonstationary perspective is lacking (Kwan, 2021; Marquart et al., 2021; Noel et al., 2021). This is important, because travelers, such as cyclists and pedestrians, have different places they pass; therefore, they have unique exposure profiles which vary in time and space (Borbet et al., 2018; Park, 2020; Heydon and Chakraborty, 2020; Kou et al., 2020; Marquart et al., 2021). These can be captured by wearable sensors (Helbig et al., 2021). Recently, research explored the subjectively perceived exposure, which is not always in line with measured exposure (Kou et al., 2020; Marquart et al., 2021; Nikolopoulou et al., 2011; Ueberham et al., 2019; Verbeek, 2018). Hence, there is a need to investigate perceived exposure. Qualitative research can be beneficial, because it allows in-depths investigations into the discrepancies in measured and perceived exposure and the situational, contextual or local elements that influence exposure perception (Noel et al., 2021).

By taking a nonstationary perspective, this study examines what influences wellbeing during active commuting trips while simultaneously taking the exposure to air pollution and noise into account. By complementing qualitative, on-the-move interviews with wearable sensors, this study aimed to (1) understand what subjective factors influenced travelers' wellbeing and experiences during daily commutes, (2) how urban dwellers perceived and were exposed to air pollution and noise and (3) how they acted to avoid exposure and improve wellbeing in traffic.

We will first give an overview of air pollution and noise exposure, risk perception and sensorial awareness (section 2). Then, the methodological approach (section 3) and results (section 4) are presented. Since the measurement of noise was affected by other influences while walking/cycling (e.g., wind), which is discussed in section 4.1 and section 5, we will focus more on the topic of air pollution in this study. Finally, we discuss what measures should be taken to improve wellbeing and address air pollution and noise on the move (section 5).

2. Literature review and framework

Commuting trips have a particular impact on people's subjective wellbeing and affect their overall performance at work or home (Chatterjee et al., 2020). Every day, urban dwellers spend approximately 4–7% of daily time in "traffic-influenced microenvironments" (Matz et al., 2018). In contrast to leisure travel, commuting trips are usually in these traffic-influenced microenvironments, are an unavoidable activity that is part of people's lives for many years, contribute profoundly to the inhaled daily doses of air pollutants or noise, and impact wellbeing (Chatterjee et al., 2020; Liu et al., 2019).

2.1. Exposure to air pollution and noise

Literature analyzing the link between travel and wellbeing is growing (De Vos, 2018). Recent studies introduced frameworks for the relation between transport, health and wellbeing, including physical activity, safety/causalities, subjective wellbeing, air pollution intake, noise exposure or urban heat (Chatterjee et al., 2020; De Vos, 2018; Mokhtarian, 2018; Nieuwenhuijsen, 2016; van Wee and Ettema, 2016).

Noise impacts physical health and causes psychological and physiological distress (Eriksson et al., 2018; Stallen, 1999; WHO, 2018). The stress reactions of noise, including road traffic noise, are annoyance, nervousness, anxiety and mood change (Gössling et al., 2019; Murphy and King, 2014; Ouis, 2001). The physiological distress comprises cardiovascular disorders, hypertension or cognitive effects (Babisch, 2008; Eriksson et al., 2018; van Kempen and Babisch, 2012). Traffic is the most severe noise source in cities (WHO, 2018). According to a study by the German Federal Environmental Agency, about 75% of the study's respondents felt annoyed by traffic noise (Rubik, 2020). Noise in afternoon hours (4pm–7pm) is especially perceived as distressing, because it disrupts supposedly relaxing situations (Schreckenberg and Guski, 2005). During their daily commutes, people are not in control of the noise source. The lack of perceived control is important for noise annoyance (Stallen, 1999). In three European cities, the average noise level exceeds 60 dB(A) in all transport modes, whereas cyclists had the highest noise exposure (Okokon et al., 2017).

The adverse health effects related to ambient air pollutants include respiratory diseases, cardiovascular diseases, cognitive impairment, cancer, asthma, hypertension and diabetes (EEA and European Environmental Agency, 2015; Alotaibi et al., 2019; Howell et al., 2019; Kelly and Fussell, 2015; Künzli et al., 2000; Sears et al., 2018). Air pollution leads to emotional and behavioral changes (Li et al., 2018), has an impact on people's moods (Lin et al., 2019; Nuyts et al., 2019) and causes increased psychological distress, mental disorders and depression (Gładka et al., 2018; Sass et al., 2017; Xue et al., 2019). Particulate matter (PM2.5) is reported to be the fifth-ranking mortality risk factor worldwide in 2015 (Cohen et al., 2017). PM from motorized traffic is inhaled in higher doses with an

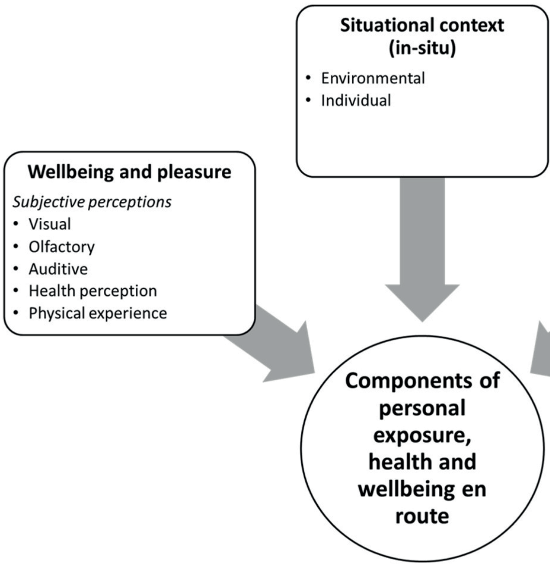

Fig. 1. Conceptual framework (based on Marquart et al., 2021): Interaction of personal exposure, health and wellbeing en route. Physical/mental health impacts from measurable air pollution and noise (state-of-the-art research on exposure), situational context (i.e., in-situ environmental situation and individual context (based on Marquart et al., 2021)), as well as wellbeing and pleasure en route, influenced by sensory awareness, health perceptions and physical experience (current study), as important factors influencing a healthy and pleasant commute. This paper specifically draws attention to the aspects of wellbeing and pleasure en route.

increasing proximity to the emitter (Cole-Hunter et al., 2012) and was measured highest for cyclists and pedestrians (Chaney et al., 2017; Okokon et al., 2017). Exposure during transport contributes to 7.8% of people's daily exposure, even though the time people spent in transit is rather little (Park, 2020).

Nevertheless, the health benefits of walking and cycling are still substantially larger than the potential risks from air pollution, and cycling contributes to a lower all-cause mortality rate in European cities (de Hartog et al., 2010; Gelb and Apparicio, 2021; Rojas--Rueda et al., 2011, 2016; Woodcock et al., 2009). If the traffic-related air pollution and noise exposure of cyclists/pedestrians is minimized, their beneficial effects for public health and overall wellbeing could be further enhanced (Reardon and Abdallah, 2013).

2.2. Sensory awareness and risk perception

The health impacts of noise or air pollution are evident. However, laypersons often neglect their exposure; they either do not express concern regarding air pollution or deny the effects (Bickerstaff, 2004). The literature on risk perception and protective actions and behavior shows that sensory awareness of risks (olfactory, auditive, visual) and the experience of physiological effects are relevant determinants of risk perception and behavior (Bickerstaff, 2004; Gatersleben and Uzzell, 2000; Lindell and Perry, 2012; Noel et al., 2021). Regarding traffic-induced air pollution and noise, sensory awareness (also called sensory perception (Deguen et al., 2012) or environmental cues (Lindell and Perry, 2012)) can be the visual appearance of dust, the smell of exhaust fumes or a high perceived exposure to noise (Gatersleben and Uzzell, 2000; Noel et al., 2021; Okokon et al., 2015). Following the Protective Action Decision Model (PADM), sensorial awareness is also decisive for protecting oneself against a risk, as well as social cues (observing the behavior of others), access to information and warning messages, and personal characteristics (physical/cognitive, vision/hearing or economic/social resources) (Lindell and Perry, 2012).

Cyclists and pedestrians are directly exposed to their environment during the journey. As conceptualized by Liu et al. (2021), the cycling experience is based on sensory awareness and social experiences, and also on spatial experiences (built environment). As sensory awareness is relevant for walking/cycling and the associated risk perception and protective actions, we draw attention to momentary sensorial awareness, as well as pedestrians'/cyclists' social and spatial experience.

2.3. Perceived and measured exposure

As presented, active mode users are exposed to air pollutants and noise. Although this link to health is evident, research is lacking on the momentary sensorial awareness of these stressors while en route. Following the "new mobilities paradigm", the embodied practice of movement and the experiences and perceptions of people during movement are of importance (Cresswell, 2010; Sheller and Urry, 2006). Positive experiences during travel can improve personal wellbeing and perceived quality of life (the ecological perspective of wellbeing) (Nordbakke and Schwanen, 2013). Recent studies presented a bias in the perceived environment and the

Table 1
Overview of the sample.

Mode of transport used during the study (n)	Gender (n)	Age (n)	Mode of transport available (household) (n)	Employment (n)	Integrate children in route (n)
Bicycle (21) **Walking + public transport** (5) **Cycling + public transport (only commuter train)** (2)	Female **(16)** Male **(12)**	21–30 **(9)** 31–40 **(8)** 41–50 **(4)** 51–60 **(5)** 61–70 **(1)** n/a **(1)**	Bicycle **(28)** Public transport ticket **(15)** Car-sharing **(13)** Car **(7)** Bicycle-sharing **(4)** Scooter-sharing **(2)** Motorbike **(1)**	Full-time **(9)** Part-time (flexible) **(12)** Part-time (non-flexible) **(2)** Self-employed **(2)** Student **(7)**	No **(21)** Yes, sometimes **(5)** Yes, always **(2)**

recorded environmental situation, referring to the high importance of dynamic spatio-temporal conditions and situational contexts (Kou et al., 2020; Marquart et al., 2021; Ueberham et al., 2019; Verbeek, 2018). Marquart et al. (2021) developed a framework conceptualizing the interaction between personal exposure, health and wellbeing while en route. According to this, the interaction is shaped by a) the physical and mental health impacts caused by objectively measurable air pollution and noise, b) the situational context and c) perceived wellbeing and pleasure while en route, influenced by subjective perceptions of personal exposure and the environment, perceived health and the physical experience (Fig. 1). This paper draws attention to wellbeing and pleasure during commute; we will examine visual, olfactory and auditive experiences, in-situ health perceptions and the physical experience of cyclists/pedestrians. Given the severe health impacts of air pollution and noise, subjective perceptions will be linked to the measured air pollution and noise levels.

3. Methods

To explore exposure and perceptions simultaneously, a mixed-methods approach was applied using qualitative interviews on the move (so called "walking interviews" or "go-/ride-alongs") and parallel measurements with wearable sensors. Go-/ride-alongs are based on ethnography as well as practice theory; they reveal subjective perceptions, sensory awareness and practices by discussing them in an explorative way while moving (Degen and Rose, 2012; Evans and Jones, 2011; Kusenbach, 2003; Kühl 2016; Pink, 2015). Based on a qualitative research design, the interviewee is understood as an 'expert' of his/her own life. Interacting with or 'following' a person in different familiar sites provides an understanding of how and why a person perceives, acts in and navigates through his/her environment (Büscher, 2011; Carpiano, 2009; Marcus, 1995). The qualitative research design is complemented by quantitative exposure measurements on the move using wearable sensors. These are beneficial to assess the dynamic exposure situations of moving people (Ma et al., 2020b; Schlink and Ueberham, 2020).

3.1. Sampling and procedure

The study took place in Berlin, Germany. Berlin is the capital of Germany with 3.6 million inhabitants (2020). The study had three recruiting phases: I. October–December 2019, II. August–October 2020 and III. October–November 2020.[1] Interviewees were recruited through social media (Twitter and snowballing), newsletters, flyers, direct contact with offices and online neighborhood networks. Therefore, different commuting routes were ensured. As an incentive, interviewees were offered personal feedback on air pollution and noise. Requirements for taking part were commuting to work with a bicycle, on foot and/or by public transport and living and working in Berlin. The participants were selected allowing for a balanced gender and age ratio. After each phase, a group discussion about experiences, measurements and risk communication was held (group discussions are the topic of a forthcoming article). We conducted three pre-tests.

In total, 28 people participated in the study. Most of them commuted by bicycle. All interviewees had a driver's license and a bicycle available, followed by public transport tickets and car-sharing. Most had flexible working hours and no children, which made it easier to choose routes and times freely. A total of 21 interviews were conducted by bicycle, five on foot (and public transport, i.e., bus, commuter train or subway) and two by bicycle and commuter train. Table 1 provides an overview.

3.2. Interview procedure

The go-/ride-along interview took place directly after work. Interviewees decided a time and place close to their work. Firstly, a sedentary introductory interview, which helped to familiarize with the situation, was conducted. The interviewee gave an overview of his/her route, health/wellbeing status and perceived air pollution and noise. Consequently, the interviewer could refer back to these

[1] The longer break in between phase I and phase II and III was due to the corona pandemic in early 2020. Interview phase II and III were after the corona pandemic outbreak, phase I before.

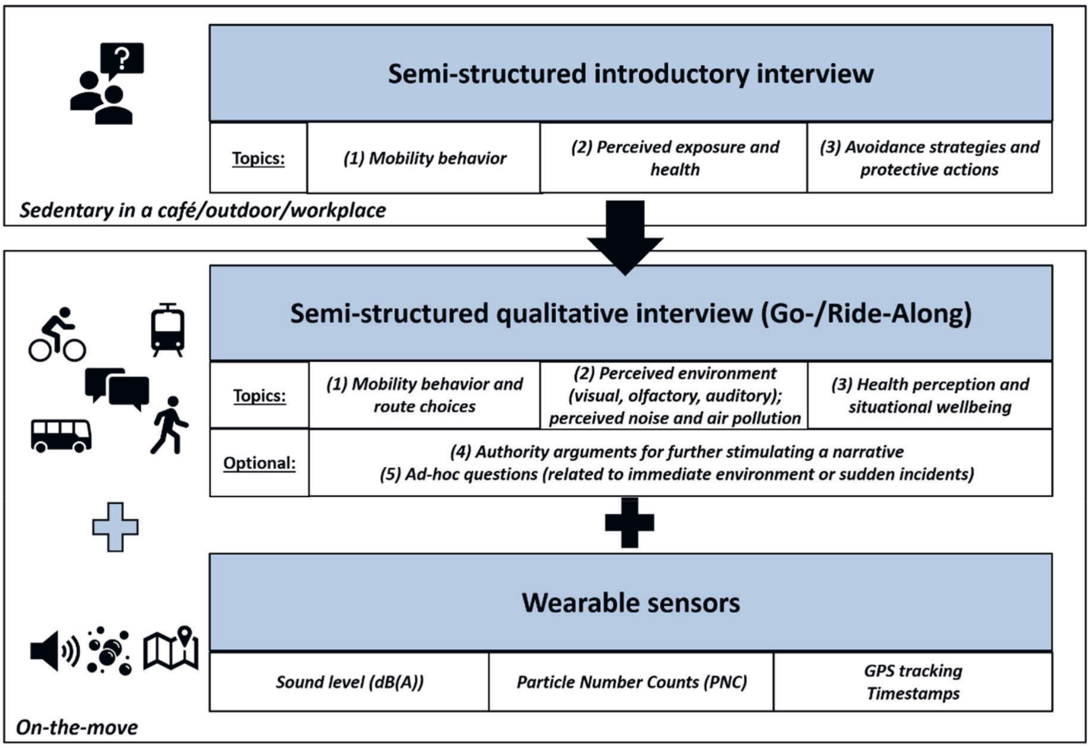

Fig. 2. Study design.

statements later on and become familiar with the forthcoming route. Directly following this, the interviewer accompanied the interviewee on the commute. The after-work commute was chosen because exposure is perceived as severe during late afternoon hours, in which relaxed activities are supposed to take place (Schreckenberg and Guski, 2005).

The go-/ride-along was conducted by bicycle or on foot (incl. public transport), as preferred by the interviewee. Meanwhile, a semi-structured interview guideline based on elements of risk perception and PADM (Lindell and Perry, 2012) (section 2) covered four topics: (1) practices while cycling/walking and route choices (*past experiences*, *protective actions, social cues*), (2) perception and experiences of the immediate environment (*sensorial awareness: auditive, visual, olfactory*), (3) health perception, mood and situational wellbeing (*threat perception, attitudes, personal characteristics*) and (4) authority arguments, air pollution and noise in general or in situ (*information, warning messages*). This stimulated the interviewees to actively think about exposure. Ad-hoc questions were asked based on the immediate environment, sudden incidents or referring to the introductory interview. The interviewer recorded her own observations.

3.3. Technical equipment

The interview questions were well known by the trained interviewer and were attached to her bicycle. For safety reasons, the interviewee and interviewer received an audio recorder and a microphone attached to the collar; hence, they could cycle/walk freely. The time that the recording started was noted. During the go-/ride-alongs, the interviewer carried wearable sensors measuring noise (dB(A), interval: 2 s, device: Motorola G3 with an external microphone and pre-installed sensing application based on Ueberham et al., 2018) and particle number count (PNC) (0.5–2.5 μm, #/ft^3, interval: 1 min, sensor: DylosLogger 1700). The devices were previously applied and validated (Ueberham and Schlink, 2018; Ueberham et al., 2019). GPS was tracked and time-stamped. Fig. 2 shows the study design.

3.4. Data analysis

In the first step, the interviews were transcribed and real-time stamps were added. The transcripts were analyzed following an inductive-deductive approach using MAXQDA2020. The coding focused on statements related to in-situ situations, based on PADM and risk perception theory, but was still open to new themes by referring to the “all is data” principle of grounded theory (Strauss and Corbin, 1996). After several rounds of coding, the coding frame resulted in (1) sensory awareness (perceived sounds, perceived air/smells, visual experiences) and perceived health/wellbeing (incl. physical experience), (2) on-site attitudes towards the

Table 2
Categories and codes, including number of mentions, that refer to momentary sensory awareness and which were retrieved during the coding process. They will be presented in detail in the respective sections.

Perceived sounds *(section 4.2.1)*		Perceived air/smells *(section 4.2.2)*		Visual experiences *(section 4.3.1 till section 4.3.3)*		Health and wellbeing *(throughout, especially section 4.3.4)*	
Positive sounds (memories)	1	Good smell (memories)	1	Dirt/dark areas	8	Safe feeling (social safety)	2
Neutral sounds	1	Neutral smells	2	Unaesthetic urban structures	8	Unsafe feeling (social safety)	6
Positive sounds (people talking)	2	Good smells (nature/water)	7	Vast view/sky visibility	10	Unhealthy	7
Positive sounds (musicians)	4	Fresh air	9	Entertainment (shops/cafés/ …)	11	Healthy	10
Quietness	40	Polluted air	42	Observe people	18	Tensions	10
Noise	49			Community/neighborhood	19	Safe feeling (traffic injuries)	14
				Aesthetics and urban form	24	Unsafe feeling (traffic injuries)	27
				Vegetation/water	49		

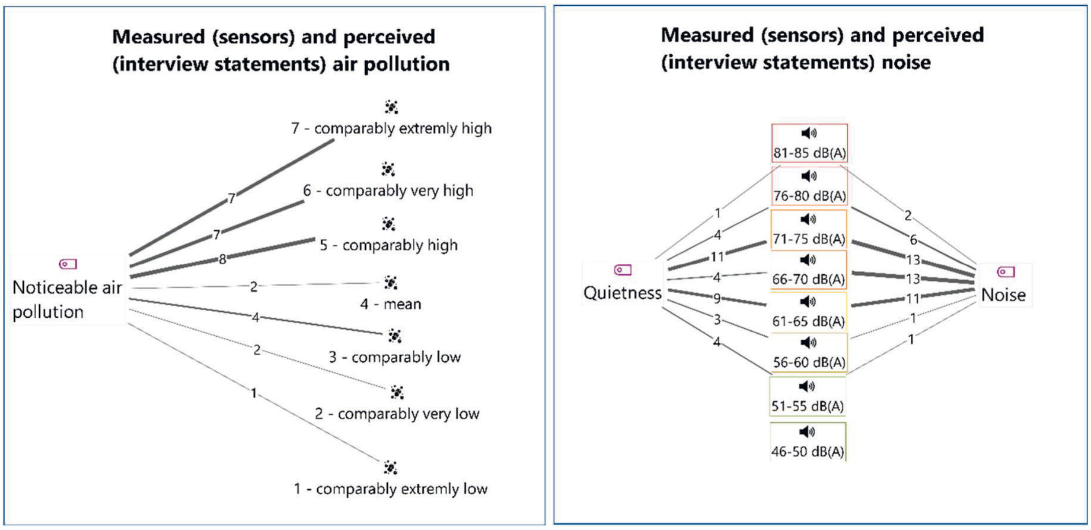

Fig. 3. Left: Comparing measured (sensors) air pollution data with perceived air pollution (interview statements on momentary noticeable air pollution). Right: Comparing measured (sensors) noise data with perceived noise/quietness (interview statements on momentary perceived noise/quietness).

environment (pleasant/unpleasant) and (3) protective practices. Then, the interviewer's observations of the built environment were coded. Relevant citations were translated from German to English.

In a second step, the wearable sensor data were merged with GPS and land-use data, and then visualized and validated in QGIS (version 3.10.3-A Coruña). For data privacy, the last/first meters of each route were cut off. In a third step, relevant codes referring to on-site situations were coded with the respective air pollution and noise data, using timestamps. For noise, the median was taken for at least 10 s when the statement was made. The noise data were classified in eight even classes ranging from 46 dB(A) to 85 dB(A). The PNC measurements, which differed each day (due to season, weather, wind, time), were classified with QGIS (version 3.10.3-A Coruña) into seven quantiles for each route, ranging from 1 (comparably extremely low) to 7 (comparably extremely high). Data were visualized using MaxQDA2020 and QGIS (version 3.10.3-A Coruña). Details of the data analysis together with information on the method are discussed for a sub-sample in Marquart et al. (2021).

4. Results

We will now present the results of the 28 go-/ride-along interviews and how they relate to the measurement data. The results are divided into four themes, based on the categories developed from the data: first, key factors influencing the commuting experience; second, perceived sounds and air; third, visual experiences; and fourth, protective practices en route. It should be noted that high sound levels do not always represent traffic-noise. They can be influenced by air flow at high speeds, leaves rustling, artificial sounds (gravel crunching, sound of bicycle), busy streets (pedestrians) or street-music, which was detected through the audio-recordings. Because of difficulties in interpreting dB(A), we decided to have a focus on air pollution and consider noise measurements with caution.

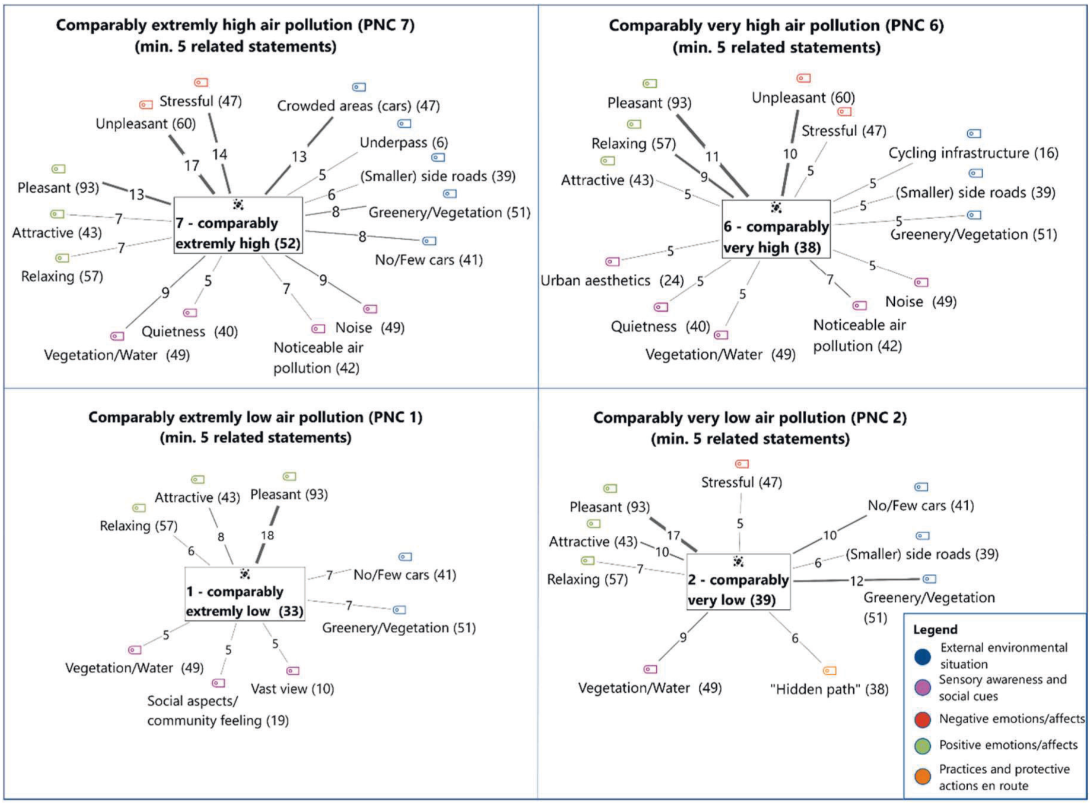

Fig. 4. Coded interview statements ("codes") during extremely high/very high and extremely low/very low measured particle number counts (for better visualization, only codes which were found at least 5 times or more are shown). The numbers in brackets represent the total number of each code as retrieved from the interview data, and the number on the lines shows how often the code was found in relation to the respective air pollution level.

4.1. Key factors influencing commuting experience

A variety of key factors for an (un)pleasant commute could be identified during the go-/ride-alongs. Most commonly participants discussed perceived noise, perceived air pollution and vegetation/water. Table 2 shows the categories we developed from the data.

The participants evaluated their environment slightly more often as pleasant than unpleasant. Vegetation/water and urban aesthetics are important for a pleasant trip, as are quietness, community feeling, places/situations of interest, entertainment, vast views and other people. Unpleasantness was related to perceived noise and air pollution and during unsafe situations. Dirty/dark areas, unaesthetic urban structures, unhealthy feelings, body tension and concerns over social safety referred to negative emotions (see Appendix A). We will now elaborate on the meaning of each category.

4.2. Perceived sounds and perceived air pollution

Air pollution was perceived most often when the PNC measurements were comparably high to extremely high; whereas at low to extremely low air pollution levels, few interviewees perceive air pollution (Fig. 3). There is no clear tendency when comparing perceived good air (fresh air or good smells) with the measurements. Looking at noise, there is only a slight tendency that the measured and perceived exposure match (Fig. 3).

During comparably extremely and very high air pollution, the interviewees perceived their environment as unpleasant or stressful 46 times, but the environment was perceived as positive 52 times (Fig. 4). Reasons for these discrepancies are, for example, vegetation/water, social cues or urban aesthetics, which can balance even highly exposed areas and make people feel pleasant en route (Fig. 4). Generally, perceived noise and perceived air pollution negatively influence the commute, which is not always in line with the measurements. We will provide detailed information in the following sections.

4.2.1. Perceived sounds

Nearly all the noise statements referred to road or rail traffic noise. Perceived noise was often related to perceived air pollution.

Interviewees reported surprise; some noticed their noise exposure the first time during the go-/ride-along (RA14,[2] RA17, RA20, RA27). Others reported sadness (RA1), annoyance/stress (RA7, RA11, RA 12, GA13, RA16, RA25, RA28), fear (RA27) or body tension related to noise (RA20):

> *"I sit here with a tense torso, and I have my handlebars tight in my hands. And actually, I am ready to jump off the bike or something like that [laughs]. […] maybe it is because of the noise, unconsciously …"* (RA20, PNC 7, on a busy road)

However, perceived noisy and busy streets were also interesting, because you can see "*so many interesting people*" or "*visually diverse*" buildings (GA15, RA22). Sometimes the interview was interrupted because of noise from a passing vehicle/train, which the interviewee noticed (GA6, RA10, GA13, RA25, RA27). Occasionally the conversation while cycling was problematic due to high noise levels, which increased awareness (RA2, RA11):

> "*You perceive the noise, because when we start talking during cycling, you notice, that you have to speak louder or scream. When I cycle by myself then I do not notice it. But in the moment of communicating you feel, 'oh man, it is so loud!', […]. Usually, I don't talk while cycling [laughs].*" (RA11, PNC 5, on a busy road)

Statements about momentary perceived quietness were stated equally often as perceived noise. Quietness was important and mostly mentioned related to vegetation (RA2, RA17, RA18, RA19, RA24, RA28) and areas without cars (RA17, RA25):

> "*I do not hear anything here! Well, of course, I hear our bicycles, I maybe hear someone laughing on a balcony, but I do not hear any cars anymore. […] it is very, very quiet."* (RA27, PNC 4)

Quietness was noticed in comparison to loud areas (GA13, GA15, RA14). Having "*short quiet sections*" integrated in the route was relaxing (RA10). You can "*soak in the peace and quiet*" before entering a busy road (RA10, RA7). Quietness was associated with "hidden paths" (RA12, RA15), in car-restricted sections (RA9, RA10, RA24) and mentioned on smaller side roads (RA5, RA27). After entering the train after a noisy busy road, interviewees noticed the quietness (GA13, GA4).

The situational context of exposure also plays a role; leaving work or seeing people do leisure activities was associated with quietness (RA11, RA22, RA25, RA28, RA28):

> "*Yes, and here it is getting quieter. The after-work time starts now. You feel it, the atmosphere, the people here doing barbecue."* (RA11, PNC 2)

Interviewees positively mentioned music en route, e.g., by musicians in the subway hall or in the park (GA4, GA6, GA8, RA28). Hearing other people's conversations on their way home was pleasant (RA24, RA27). Although loud sounds were captured by the noise measurement device, their source is important for evaluating them as noises or positive sounds.

4.2.2. Perceived air/smells

Air pollution, sensed as a "*bad smell*" or seeing "*exhaust fumes*", was mostly related to busses (RA1, RA2), trucks (RA11), motorbikes (RA17, RA 25), busy roads (RA 2, RA5, RA10, RA20, GA13, RA20), closeness to freeways (RA19), being in traffic jams and by traffic lights (RA10, RA26, RA28) or being underneath an underpass (RA16, RA28):

> "*If I have a moment time, I would pull up my mask. Otherwise I would have taken my scarf. Because, […] you can really smell it, if you are under there [points at the underpass], you have the feeling, that all fresh air is gone and the rest is full of exhaust fumes.*" (RA28, PNC 7)

Having children influenced air pollution perception, because parents felt responsible for protecting them (RA7, RA20):

> "*This is one of those situations where I am in the middle of the traffic and I think, that can't be it. If my child sits here as well [in her cargo bike], it would be right on the height of the exhaust pipes!*" (RA20, PNC 3)

Generally, the interviews showed that knowledge about air pollution is lacking. Interviewees think about air pollution but do not know how it impacts health or how to lessen exposure (RA24, RA26):

> "*This exhaust fume smell annoys me […]. But I honestly don't really know what the direct impact is on my fitness level or if it is something, which rather evolves over time. That my health is impacted by these emissions over time …"* (RA24, PNC 7).

> "*[…] but I pass the cars [at the waiting line at a traffic light] so that I don't have to stand behind them, because I think, then I would inhale more exhaust fumes. But, meanwhile, I am asking myself if it is not equally bad [in front of the line at the main intersection], with all the cars driving from the intersecting street?*" (RA26, PNC 6, busy intersection)

Perceived fresh and good air was mostly associated with vegetation/water (RA2, RA10, RA11, RA24, RA28). Wind was perceived as fresh air, despite sometimes measurably high PNC (RA7, GA15). Commonly, interviewees reported that positive smells, e.g., gardens, trees, nature, water or rain, were important for their wellbeing (RA10, RA11, RA17, RA25, RA26, RA28).

4.3. Visual experience: Nature, urban form and social cues

As shown, sometimes the measured and the perceived exposure are in line, yet they often differ. Other factors influence wellbeing

[2] RA refers to "Ride-Along" (i.e. cyclist)/GA refers to „Go-Along" (i.e. pedestrian) incl. participant number.

[3] Green/blue spaces derived from Geoportal Berlin/FNP, https://fbinter.stadt-berlin.de/fb/index.jsp, dl-de/by-2-0; Basemap data © OpenStreetMap contributors, www.openstreetmap.org/copyright (this refers to all maps in the article).

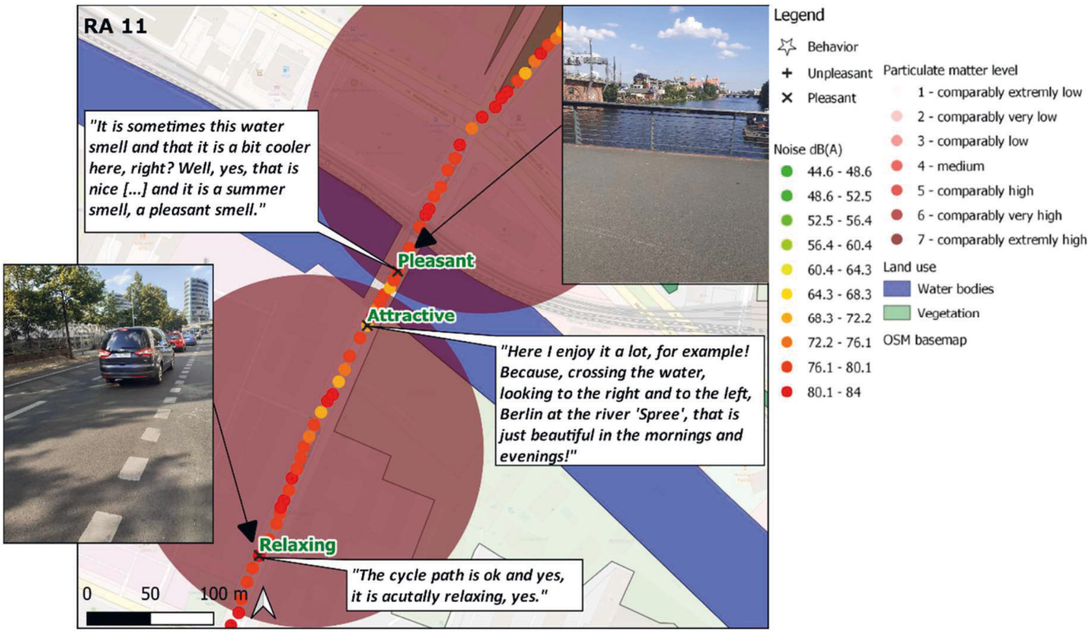

Fig. 5. Differences in perceived and measured exposure and the importance of the surrounding environment, i.e., bodies of water (RA11).[3]

during high exposure and can even balance negative traffic situations, especially nature, interesting urban forms and social cues (Fig. 4).

4.3.1. Nature

Commuting through parks, alongside trees, greenery or urban forests was essential throughout all interviews. It highly influenced a pleasant commute. Nature calms down and brings quietness during the journey (RA2), compared to stressful roads (RA5). Route sections with greenery were considered the "*most beautiful part of the trip*" (RA7) and seeing "*the sun going down*" (RA7, RA19, RA22) or the seasons changing (RA7, RA10, RA27, RA28) improved the journey. Areas with greenery resulted in "*holiday feelings*" (RA16). Animals enhance the journey; interviewees liked seeing foxes, sheep, rabbits (RA16, RA21) or a boar in the evening (RA 23). In greenery you "*don't really notice that you are in a big city*" (RA24) and can "*leave the big city behind*" (RA26). An interviewee in the train enjoyed passing greenery (GA15). Even trees or grass verges on the street improved the trip (RA10, RA11, RA17, RA19, RA20, RA22, RA25, RA27, RA28, GA4, GA6, GA8, GA 15):

> "*[…] Here you can see the seasons changing and the nature. For example, I really enjoyed it is spring, to see the grass growing, then seeing how it is cut, and how the people were sitting then on the bale of hay. […] I enjoy watching the time go by like that. […] that I can witness that has a big influence on me!*" (RA28, PNC 2)

Moreover, green spaces improve perceived health en route (RA18, RA24):

> "*Here it is nice. I know, there is green to the right and everything is getting quieter. You know the heart rate slows down.*" (RA 18, PNC 7).

Water was important as well (RA11, RA18, RA19). Looking over the water is regarded as beautiful (RA11, RA19), even though PNC numbers were high on a busy road (Fig. 5). Fountains made busy roads pleasant (RA11, RA22, GA8).

4.3.2. Urban form and aesthetics

In general, aesthetic buildings improve the commuting experience (RA2, RA10, RA11, RA16, RA18, RA21, RA22, RA25, RA26, RA27, GA6, GA8, GA13). Historical sites, e.g., the '*Berlin Wall*' (RA10), the castle '*Bellevue*' (RA26), historical parks (RA21), historical street lanterns (GA6), old/historical buildings (RA11, RA16, RA25, GA13, GA15), abandoned buildings (RA25), churches (RA27) and landmarks (RA18) were positively mentioned. Public transport users enjoy nicely designed subway stations (GA4, GA6, GA8). Interesting urban forms make the journey pleasant (GA15, RA27):

> "*I like places which have this 'flair', which have a history and where it is not like […] these normed houses, which all look the same. Every house has a story to tell.*" (GA15, PNC 6)

> "*Here are these buckets, which are painted so nicely. And on one side it says 'lachs', which I don't understand but I think it is funny.*" (RA27, PNC 4)

Urban structures that allow a vast view improve the commute (RA7, R11, RA16, RA17, RA18, RA21, RA24, RA28). Urban forms

Fig. 6. Example of two pedestrians living in the same neighborhood. The train station with high PNCs is perceived as unpleasant, whereas the shopping street, at an equal PNC level, is perceived as pleasant and enjoyable. The side roads, with comparably high PNCs, were also perceived as pleasant/relaxing due to the neighborhood feeling and people along the route.

dedicated to cyclists and nature were related to feeling safe; cycling infrastructure, no/few cars, smaller side roads or greenery improved subjective safety (GA8, RA12, RA14, RA19, RA20, RA24, RA26, RA26, RA27).

4.3.3. Social cues

Community feelings enhanced the commute (RA10, RA23, RA24, RA25, RA27, RA28). Interviewees enjoy passing lively areas with cafés/restaurants and small shops (RA22, RA24, RA27, GA6, GA15). Other interviewees enjoyed passing playgrounds and meeting neighbors (RA23, GA13). Generally, arriving in one's own neighborhood was positive; people felt attached to it (RA24, RA25, RA28, GA13, GA15). In particular, pedestrians in smaller, busy shopping roads talked about the feeling of their neighborhoods, despite the traffic/air situation there (Fig. 6).

Seeing other people do leisure activities (e.g., in parks/cafés) was a strong social aspect that made the trip enjoyable (RA24, RA27, RA28). In particular, that "*you can linger here*" and "*there is a place for it*" in the city was important (RA24, RA28):

> "*That [people sitting in the park] also brings me a little bit in the mood. They trigger me […].*" (RA24, PNC 1, in a park)

> "*The people here are way more relaxed. Everyone has his own place here. And even if the people fly a kite or children play here […], it is a completely different feeling [compared to the busy road before].*" (RA28, PNC 4, in a park)

Passing people aroused interest in fellow urban dwellers and increased the feeling of belonging to the city (RA5, RA19, RA20, RA21, RA22, RA24, RA26, RA27, RA28, GA4, GA13). Interviewees enjoyed seeing gardeners in allotment gardens (RA10, RA19), people in their free time (RA24, RA28, GA13), skateboarding kids (RA27), soldiers at the diplomat offices (RA26) or truck drivers at the gas station (RA19). Watching people improves the journey in unattractive routes (RA22, RA26) or calms commuters down in the train (GA4):

> "*Even though, in this street, the noise exposure is very high and it is super full, you see interesting people! That is also something positive here.*" (RA22, PNC 4, busy road).

4.3.4. Dirty/dark areas, and unaesthetic and dangerous urban forms

Interviewees also described negative experiences. Busy intersections were "*concrete deserts*" (RA12) or a prison, and old hostels

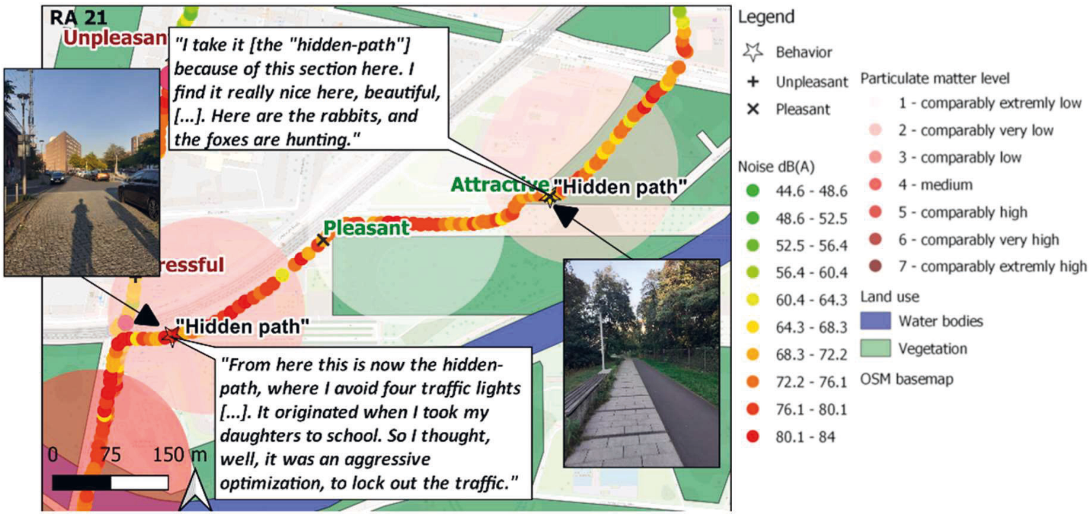

Fig. 7. Example of "hidden paths", made by Ride-Along 21. The PNC level in the hidden paths was comparably extremely low, and the interviewee perceived it as pleasant and attractive. The noise measurements should be interpreted with caution, because the cobblestones, leaves rustling or wind may have influenced the sometimes high dB(A) measurements in these car-free hidden paths.

were "*ugly*" to pass (RA26). In narrow streets with high buildings, interviewees felt cramped (RA17). Inner-city areas with artificial lights seemed "*not built for people living in the city*" (GA8). Garbage or dirt impaired the commute experience (RA25, RA28, GA15). Darkness in parks, streets without light or bleak areas were perceived as unattractive/dangerous (RA25, RA27, GA6). Concerns about social safety were stated in three subway stations in relation to dodgy persons (GA4, GA6, GA13). Feeling unsafe regarding traffic injuries was stated in crowded areas (cars, busses or cyclists), at intersections, with parking cars, on smaller side roads or with missing cycling infrastructure (RA2, RA3, RA9, RA11, RA12, RA14, GA15, RA16, RA18, RA19, RA20, RA25, RA26, RA27, RA28). Feeling unsafe was related to perceived noise or unaesthetic urban structures (RA12, RA16, RA20, RA27):

> "*Hearing that many cars are coming behind me, that is why I usually wear headphones. Because it scares me a lot, if I hear how close they are coming and how close they are.*" (RA 25, PNC 7, highly trafficked road)

4.4. Protective practices en route

Accompanying cyclists/pedestrians gave the opportunity to ask ad-hoc questions about commuting practices. Four protective practices could be identified: increasing speed to avoid unpleasant areas, suppressing/ignoring exposure, increasing distance from cars/emitters, holding one's breath/covering one's nose and using hidden paths.

Hidden paths were important and knowing them was essential (RA1, RA2, RA3, RA5, RA, RA10, RA,12, RA16, RA17, RA18, RA19, RA20, RA21, RA25, RA27, RA28, GA8, GA13, GA15):

> "*[…] here again is a small road, you ride behind the backside of this residential area. […] I have a colleague, […] and he always went here […], I asked him one day, 'Tell me, where did you go over there?' […] And then I followed him and I have discovered this path here and since then I always take this way.*" (RA12, PNC 3, greenery, pedestrian path, no cars)

Hidden paths often included no/few cars, side roads and greenery/water. The PNC measured are mostly low (16 times below median, 6 times higher). Participants perceived hidden paths as quiet (RA8, RA19, RA27, GA15) and they enjoyed the vegetation/water (RA5, RA7, RA10, RA12, RA21, RA28, GA15) (Fig. 7). The knowledge of hidden paths was important and gained through peers, e.g., through one's husband (RA7), colleagues' suggestions (RA12, GA15, RA16) or own experiences (RA17, RA21, RA27). Some searched for routes away from car-dedicated streets (Fig. 7) (RA12, RA19, RA20, RA21).

Participants increased speed to avoid unpleasant areas (RA1, RA17, RA20, RA28) or distance from cars/emitters (RA1, RA2, RA7, RA10, RA12, RA26, RA27). Three participants (RA5, RA10, RA28) "*breathe flatly*", "*try to hold the breath*" or "*pull up the mask*". Other participants cope with the stressors by suppressing/ignoring exposure, e.g., emotionally/mentally, or using headphones (RA1, RA2, RA5, RA10, RA14, RA23, RA26, RA27, GA13):

> "*It is definitely an extreme noise emission. Before it was really quiet, at the parking space in front of Ikea, but here it is crazy loud. But I don't really pay attention to it. I suppress it. It is crazy, right?*" (RA14, on a bridge over the highway).

5. Discussion

In this study, we investigated cyclists' and pedestrians' personal exposure, wellbeing and practices during their commutes. We examined the perceived and measured exposure to air pollution and noise while on the move as well as sensory awareness, social cues and the built environment.

5.1. Sensory awareness of air pollution and noise

In line with previous studies (de Souza et al., 2020; Kou et al., 2020; Ueberham et al., 2019; Verbeek, 2018), this study showed no clear relationship between momentary perceived and measured noise. Loud sounds are not always perceived as noise and people talking, leaves rustling or music may produce high sound levels, but the situation is perceived as pleasant (see also Marquart et al., 2021). Additionally, the situational context is important; people are less disturbed by noise when doing recreational activities (Kou et al., 2020), e.g., after-work activities and commuting home. However, the interviewees emphasized the importance of perceived quietness (section 4.2). It seems that the term "quietness" is related to car-free situations or natural environments, rather than the actual sound levels. Cycling/walking along a green space or aesthetic buildings influences perceived noise and can help ignore the negative impacts of road traffic noise nearby (Szeremeta and Zannin, 2009). Perceived noise related to motorized traffic or stressful traffic situations was perceived as unpleasant. As shown by Becker et al. (2013), people love quiet, calm places and hate loud areas which are perceived as hectic and "man-made". Our study shows that busy but interesting "man-made" social environments (e.g., streets with cafés/shops) can be perceived as positive, albeit they may be measurably noisy. Overall, this suggests that the quality of noise and its subjective interpretation is very important even if the sound level is high and other built and non-built environmental factors can balance noise exposure. A people-centered approach for noise exposure research is important, and the perceptions, actions and surroundings of urban dwellers on the move should be considered.

As for air pollution, participants' perceptions were partly in line with the measurements. Measured air pollution has a greater influence on activity satisfaction than noise (Ma et al., 2020a). Although noise as a threat is rather suppressed by the interviewees (section 4.2/4.4), the visual cues of exhaust fumes or bad smells can be sensed and influence perception (Nikolopoulou et al., 2011; Noel et al., 2021). This decreases wellbeing en route. Sensory awareness plays a role in risk perception (Bickerstaff, 2004; Noel et al., 2021; Oltra et al., 2017), protective actions (Lindell and Perry, 2012) and commuting experience (Degen and Rose, 2012). We could show that sensing air pollution visually or olfactorily lowers commuting pleasure (section 4.2). Thereby, our participants, in line with previous studies, felt powerless against this ubiquitous risk (Heydon and Chakraborty, 2020; Oltra et al., 2017). To tackle this, more work on the impacts of visual cues of traffic-related air pollution on health perception, wellbeing and mobility practices is needed. Perceived and measured air pollution in traffic-environments needs to receive greater attention to protect cyclists and pedestrians.

5.2. Importance of urban space and social cues for exposure perception

Sensory awareness (i.e., sensescapes) has long been neglected in research, but it has gained increasing attention (Blitz, 2021; Degen and Rose, 2012; van Duppen and Spierings, 2013). In line with Blitz (2021), Nikolopoulou et al. (2011) and van Duppen and Spierings (2013), this study stresses the importance of perceived environmental stimuli on the move and the influence of the built and non-built environment.

As for the built environment, walking/cycling along water and near vegetation plays a key role for a pleasant commute (McArthur and Hong, 2019; Vich et al., 2019). People enjoy seeing greenery/water, and their positive smells and perceived quietness. Even when noise or air pollution are high, greenery/water can profoundly improve commuting experiences and is a decisive factor for choosing hidden paths (section 4.3.1/4.4). Green spaces improve physical health (Twohig-Bennett and Jones, 2018) and can lower depression symptoms (Roberts and Helbich, 2021). Even a small bit of greenery/water along the route increases wellbeing (section 4.3.1) and is significant for route satisfaction (Jensen, 2007; Vich et al., 2019). Strongly prioritizing greenery and water in urban planning is desirable. Moreover, aesthetic route environments are important for bicycle/pedestrian commuting (Stefansdottir, 2014; Van Dyck et al., 2012; Wahlgren and Schantz, 2012). Non-natural aesthetical factors, such as diverse urban areas, urban sights (e.g., graffiti) or historical buildings, create curiosity and interest (section 4.3.2). Cycling and walking environments should not only be healthy and safe, but also interesting and stimulating. Even in highly trafficked areas, interesting sites improve the commute. Nevertheless, dirt and dark areas were unpleasant, similar to Blitz (2021), and waiting at traffic lights next to motorized traffic increased perceived exposure (section 4.3.4). Referring to Liu et al. (2021), future research could investigate cyclist's perceived waiting time at traffic lights, especially when being next to emitters. Giving higher priority to a green, interesting and clean built environment with low pollution is important for improving cycling/walking.

As for non-built environmental factors, community feeling was important. Similar to van Duppen and Spierings (2013), interviewees referred to their familiar neighborhood when entering their home district. Community feeling was related to places where people take ownership of their city and create natural/community-related space (section 4.3.3). They were characterized by sportsgrounds/playgrounds, parks, little shops, cafés and bars. Even though these areas can have high sound levels (people talking) or air pollution (low air exchange), participants enjoyed them. Generally, people doing leisure activities along the route improves the commute. Implementing open public space where people can do leisure activities and take ownership of their city (e.g., urban gardens) along cycling/walking routes is needed. This has rarely been discussed in cycling literature and should further be investigated.

By complementing these rather subjective evaluations with measurements, we can obtain a comprehensive understanding of how a pleasant and healthy route environment should look. This study has extended the conceptual framework (section 2) and enriched it

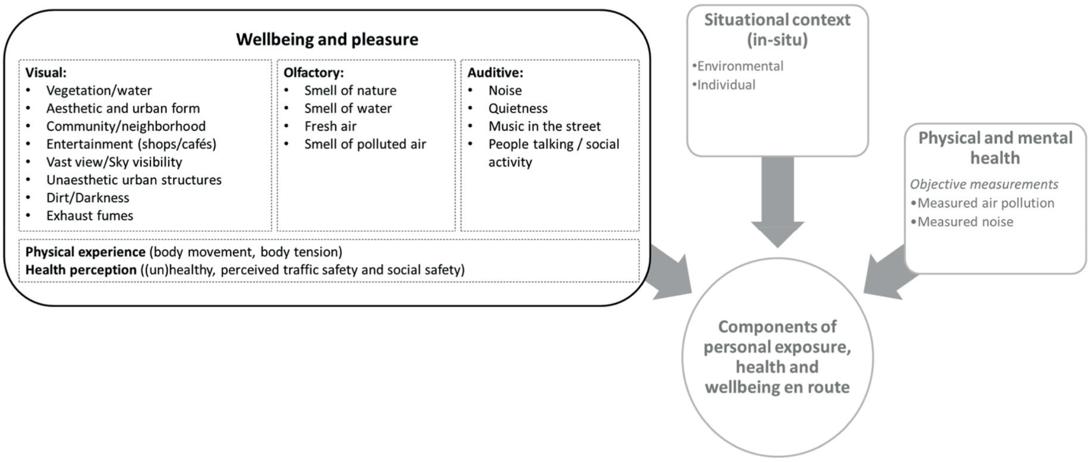

Fig. 8. Extended conceptual framework for personal exposure, health and wellbeing en route (based on Fig. 1), enriched with the results obtained in the present study.

with subjective perceptions and sensory awareness that shape wellbeing and the pleasure of commuting (Fig. 8).

5.3. Methodological benefits and limitations

This study has limitations. Firstly, in contrast to low/emerging cycling cities, Berlin is increasingly implementing bicycle infrastructure due to the mobility act from 2018 (SenUVK, n.d.) and people increasingly cycle (SenUVK, 2017). Cycling perceptions and behavior differ in emerging and established cycling cities (Chataway et al., 2014). For a low/emerging cycling city, the focus may need to be on a cyclist's fear of traffic and infrastructure (Desjardins et al., 2021), complemented by other sensory awareness factors. Secondly, the air pollution device measured particulate matter (PM). Sensors measuring multiple pollutants could be applied. Moreover, measuring noise with portable sensors is challenging, as wind or external factors influence the measurement. For documenting traffic-related noise, special noise sensors including frequencies could be applied. Lastly, as discussed by Tomsho et al. (2019), vulnerable groups, children and older people, for whom exposure is more severe, were not easily reached. Our sample comprised healthy adults aged 20–70, who took notice of the call for participants. They might not represent people who are most in need of exposure communication. Vulnerable groups need to receive greater attention in on the move exposure research. For further discussions on methodological benefits/limitations, see Marquart et al. (2021).

6. Conclusion

This study has presented how noise and air pollution are perceived en route and how they negatively influence cyclists'/pedestrians' commuting experience. However, the objectively measured exposure does not always match the individual's perception. To some extent, other factors, such as greenery, water or vibrant urban areas, are more influential for a pleasant commute. This underlines that green and blue elements or public places are of utmost importance in the city and can balance negative factors such as noise and air pollution.

From an urban planning perspective, this emphasizes the need for greenery and water as essential urban planning instruments to create healthy cities. At the same time, aesthetic buildings seem to make walking and cycling attractive. It is important to promote and preserve urban attractions to make active mobility a pleasant activity. In addition, vibrant places with people engaged in recreational activities have a positive effect. It is a matter of creating appropriate places where people can spend time and engage in public space. This improves the commuting experience as urban dwellers cycle/walk through their "own" city. It also underlines that walking and cycling operate according to a different logic than motorized transport modes. Active mobility is not just about getting from A to B; it is also about experiencing public space and the people who spend time there. Positive experiences during travel can influence personal wellbeing and perceived quality of life (ecological perspective of wellbeing) (Nordbakke and Schwanen, 2013).

However, even if greenery, water, and vibrant places can improve wellbeing and perceived health in polluted areas, it is still crucial to tackle noise and air pollution in cities. The study shows that people do not always assess the negative impact of noise and air pollution, but feel exposed to them. This makes it difficult for people to protect themselves. In addition, there are often not a lot of alternative route options. First and foremost, policies and planning need to lower harmful noise and air pollution. Subsequently, the individual motivation to protect oneself from pollution can be addressed. Routing apps for smartphones could indicate individual exposure and suggest less polluted and more pleasurable routes, including greenery, interesting sites or community areas. Information is central for risk perception and protective actions (Bickerstaff, 2004; Lindell and Perry, 2012). Exposure information can empower protective actions; however, it can also lead to resignation (Becker et al. 2021). Future research should investigate information needs in terms of air pollution, noise or pleasurable routes. For planning healthy and pleasant active mobility, the objectively measured exposure, the subjectively perceived exposure and sensorial experiences, social cues and situational contexts need to be considered.

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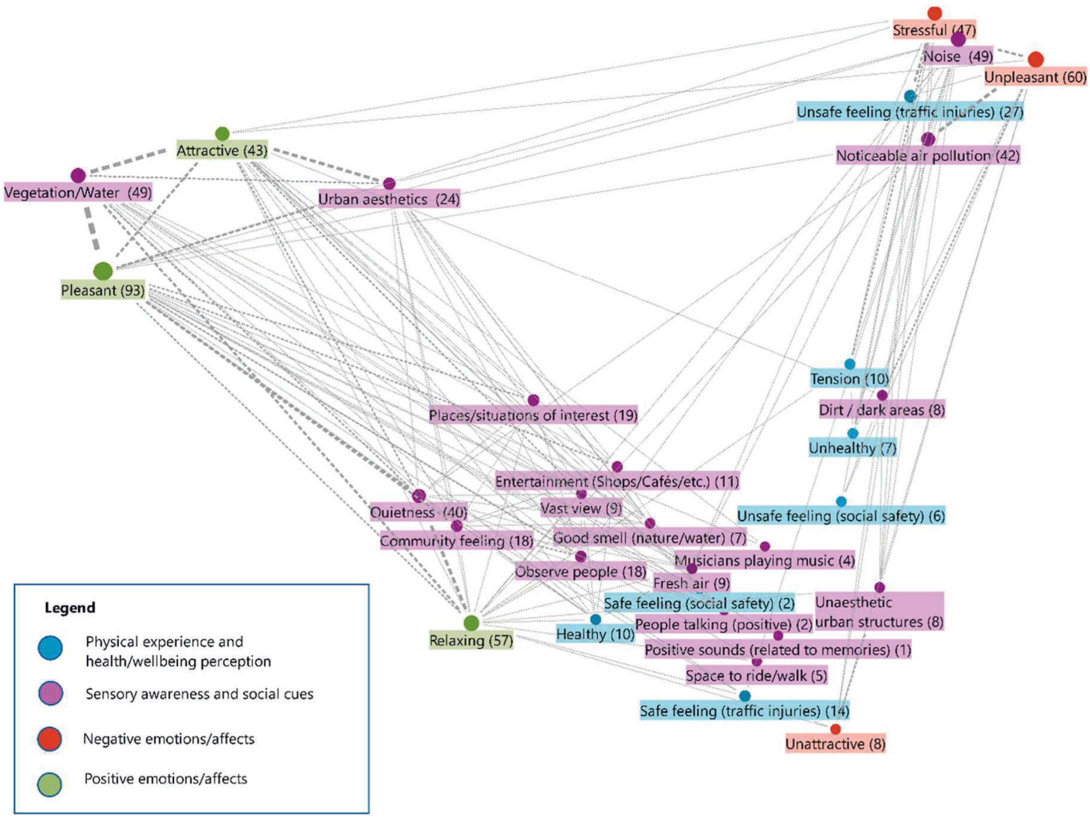
Appendix A

Relationships of codes related to sensory awareness/social cues, perceived health and wellbeing and momentary environmental evaluation (based on MaxQDAs Code Map). The closer the codes are to one another, the more often they were stated together (in relation to one another); the more apart they are, the less often they were stated together. The thickness of the line refers to the number of times they were mentioned together, and the numbers refers to the total number of statements referring to the respective code. Note that the less often a code was mentioned, the less significant the relations are.



References

Alotaibi, R., Bechle, M., Marshall, J.D., Ramani, T., Zietsman, J., Nieuwenhuijsen, M.J., Khreis, H., 2019. Traffic related air pollution and the burden of childhood asthma in the contiguous United States in 2000 and 2010. Environ. Int. 127, 858–867. https://doi.org/10.1016/j.envint.2019.03.041.

Apparicio, P., Carrier, M., Gelb, J., Séguin, A.-M., Kingham, S., 2016. Cyclists' exposure to air pollution and road traffic noise in central city neighbourhoods of Montreal. J. Transport Geogr. 57, 63–69. https://doi.org/10.1016/j.jtrangeo.2016.09.014.

Babisch, W., 2008. Road traffic noise and cardiovascular risk. Noise Health 10, 27–33. https://doi.org/10.4103/1463-1741.39005.

Becker, M., Caminiti, S., Fiorella, D., Francis, L., Gravino, P., Haklay, M.M., Tria, F., 2013. Awareness and learning in participatory noise sensing. PLoS One 8 (12), e81638. https://doi.org/10.1371/journal.pone.0081638.

Becker, A.M., Marquart, H., Masson, T., Helbig, C., Schlink, U., 2021. Impacts of personalized sensor feedback regarding exposure to environmental stressors. Curr. Pollut. Rep. 7, 579–593. https://doi.org/10.1007/s40726-021-00209-0.

Bickerstaff, K., 2004. Risk perception research: socio-cultural perspectives on the public experience of air pollution. Environ. Int. 30 (6), 827–840. https://doi.org/10.1016/j.envint.2003.12.001.

Blitz, A., 2021. How does the individual perception of local conditions affect cycling? An analysis of the impact of built and non-built environment factors on cycling behaviour and attitudes in an urban setting. Travel Behav. Soc. 25, 27–40. https://doi.org/10.1016/j.tbs.2021.05.006.

Borbet, T.C., Gladson, L.A., Cromar, K.R., 2018. Assessing air quality index awareness and use in Mexico City. BMC Publ. Health 18 (1). https://doi.org/10.1186/s12889-018-5418-5.

Büscher, M., 2011. In: Mobile methods. Abingdon, Oxon [u.a.] : Routledge, Abingdon, Oxon [u.a.]. Routledge.

Carpiano, R.M., 2009. Come take a walk with me: the "Go-Along" interview as a novel method for studying the implications of place for health and well-being. Health Place 15 (1), 263–272. https://doi.org/10.1016/j.healthplace.2008.05.003.

Chaney, R.A., Sloan, C.D., Cooper, V.C., Robinson, D.R., Hendrickson, N.R., McCord, T.A., Johnston, J.D., 2017. Personal exposure to fine particulate air pollution while commuting: an examination of six transport modes on an urban arterial roadway. PLoS One 12 (11), e0188053. https://doi.org/10.1371/journal.pone.0188053.

Chataway, E.S., Kaplan, S., Nielsen, T.A.S., Prato, C.G., 2014. Safety perceptions and reported behavior related to cycling in mixed traffic: a comparison between Brisbane and Copenhagen. Transport. Res. F Traffic Psychol. Behav. 23, 32–43. https://doi.org/10.1016/j.trf.2013.12.021.

Chatterjee, K., Chng, S., Clark, B., Davis, A., De Vos, J., Ettema, D., Reardon, L., 2020. Commuting and wellbeing: a critical overview of the literature with implications for policy and future research. Transport Rev. 40 (1), 5–34. https://doi.org/10.1080/01441647.2019.1649317.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389 (10082), 1907–1918. https://doi.org/10.1016/s0140-6736(17)30505-6.

Cole-Hunter, T., Morawska, L., Stewart, I., Jayaratne, R., Solomon, C., 2012. Inhaled particle counts on bicycle commute routes of low and high proximity to motorised traffic. Atmos. Environ. 61, 197–203. https://doi.org/10.1016/j.atmosenv.2012.06.041.

Cresswell, T., 2010. Towards a politics of mobility. Environ. Plann. Soc. Space 28 (1), 17–31. https://doi.org/10.1068/d11407.

de Hartog, J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118 (8), 1109–1116. https://doi.org/10.1289/ehp.0901747.

de Souza, T.B., Alberto, K.C., Barbosa, S.A., 2020. Evaluation of noise pollution related to human perception in a university campus in Brazil. Appl. Acoust. 157, 107023. https://doi.org/10.1016/j.apacoust.2019.107023.

De Vos, J., 2018. Towards happy and healthy travellers: a research agenda. J. Trans. Health 11, 80–85. https://doi.org/10.1016/j.jth.2018.10.009.

Degen, M.M., Rose, G., 2012. The sensory experiencing of Urban design: the role of walking and perceptual memory. Urban Stud. 49 (15), 3271–3287. https://doi.org/10.1177/0042098012440463.

Deguen, S., Ségala, C., Pédrono, G., Mesbah, M., 2012. A new air quality perception scale for global assessment of air pollution health effects. Risk Anal. 32 (12), 2043–2054. https://doi.org/10.1111/j.1539-6924.2012.01862.x.

Desjardins, E., Apatu, E., Razavi, S.D., Higgins, C.D., Scott, D.M., Páez, A., 2021. "Going through a little bit of growing pains": a qualitative study of the factors that influence the route choice of regular bicyclists in a developing cycling city. Transport. Res. F Traffic Psychol. Behav. 81, 431–444. https://doi.org/10.1016/j.trf.2021.06.005.

EEA, 2015. Air quality in Europe – 2015 report. In: European Environmental Agency (EEA) (Ed.), Technical Report. https://doi.org/10.2800/62459, 5/2015.

Eriksson, C., Pershagen, G., Nilsson, M., 2018. In: Biological Mechanisms Related to Cardiovascular Andmetabolic Effects by Environmental Noise. Copenhagen. Retrieved from. https://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2018/biological-mechanisms-related-to-cardiovascular-and-metabolic-effects-by-environmental-noise. (Accessed 30 August 2021).

Evans, J., Jones, P., 2011. The walking interview: methodology, mobility and place. Appl. Geogr. 31 (2), 849–858. https://doi.org/10.1016/j.apgeog.2010.09.005.

Gatersleben, B., Uzzell, D., 2000. The risk perception OF transport–generated air pollution. IATSS Res. 24 (1), 30–38. https://doi.org/10.1016/S0386-1112(14)60015-7.

Gelb, J., Apparicio, P., 2021. Cyclists' exposure to atmospheric and noise pollution: a systematic literature review. Transport Rev. 1–24. https://doi.org/10.1080/01441647.2021.1895361.

Gładka, A., Rymaszewska, J., Zatoński, T., 2018. Impact of air pollution on depression and suicide. Int. J. Occup. Med. Environ. Health 31 (6), 711–721. https://doi.org/10.13075/ijomeh.1896.01277.

Gössling, S., Humpe, A., Litman, T., Metzler, D., 2019. Effects of perceived traffic risks, noise, and exhaust smells on bicyclist behaviour: an economic evaluation. Sustainability 11 (2), 408. https://doi.org/10.3390/su11020408.

Hänninen, O., Knol Anne, B., Jantunen, M., Lim, T.-A., Conrad, A., Rappolder, M., null, n., 2014. Environmental burden of disease in Europe: assessing nine risk factors in six countries. Environ. Health Perspect. 122 (5), 439–446. https://doi.org/10.1289/ehp.1206154.

Helbig, C., Ueberham, M., Becker, A.M., Marquart, H., Schlink, U., 2021. Wearable sensors for human environmental exposure in Urban settings. Curr. Pollut. Rep. https://doi.org/10.1007/s40726-021-00186-4.

Heydon, J., Chakraborty, R., 2020. Can portable air quality monitors protect children from air pollution on the school run? An exploratory study. Environ. Monit. Assess. 192 (3), 195. https://doi.org/10.1007/s10661-020-8153-1.

Howell, N.A., Tu, J.V., Moineddin, R., Chen, H., Chu, A., Hystad, P., Booth, G.L., 2019. Interaction between neighborhood walkability and traffic-related air pollution on hypertension and diabetes: the CANHEART cohort. Environ. Int. 132, 104799. https://doi.org/10.1016/j.envint.2019.04.070.

Jensen, S.U., 2007. Pedestrian and bicyclist level of service on roadway segments. Transport. Res. Rec. 2031 (1), 43–51. https://doi.org/10.3141/2031-06.

Kelly, F.J., Fussell, J.C., 2015. Air pollution and public health: emerging hazards and improved understanding of risk. Environ. Geochem. Health 37 (4), 631–649. https://doi.org/10.1007/s10653-015-9720-1.

Kou, L., Tao, Y., Kwan, M.-P., Chai, Y., 2020. Understanding the relationships among individual-based momentary measured noise, perceived noise, and psychological stress: a geographic ecological momentary assessment (GEMA) approach. Health Place 64, 102285. https://doi.org/10.1016/j.healthplace.2020.102285.

Kühl, J., 2016. Walking Interviews als Methode zur Erhebung alltäglicher Raumproduktionen. Eur. Reg. 23 (2), 35–48. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-51685-8.

Künzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Sommer, H., 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. Lancet 356 (9232), 795–801. https://doi.org/10.1016/s0140-6736(00)02653-2.

Kusenbach, M., 2003. Street phenomenology: the go-along as ethnographic research tool. Ethnography 4 (3), 455–485. https://doi.org/10.1177/146613810343007.

Kwan, M.P., 2021. The stationarity bias in research on the environmental determinants of health. Health Place 70, 102609. https://doi.org/10.1016/j.healthplace.2021.102609.

Li, Y., Guan, D., Tao, S., Wang, X., He, K., 2018. A review of air pollution impact on subjective well-being: survey versus visual psychophysics. J. Clean. Prod. 184, 959–968. https://doi.org/10.1016/j.jclepro.2018.02.296.
Lin, W.-H., Pan, W.-C., Yi, C.-C., 2019. "Happiness in the air?" the effects of air pollution on adolescent happiness. BMC Publ. Health 19 (1), 795. https://doi.org/10.1186/s12889-019-7119-0.
Lindell, M.K., Perry, R.W., 2012. The protective action decision model: theoretical modifications and additional evidence. Risk Anal. 32 (4), 616–632. https://doi.org/10.1111/j.1539-6924.2011.01647.x.
Liu, Y., Lan, B., Shirai, J., Austin, E., Yang, C., Seto, E., 2019. Exposures to air pollution and noise from multi-modal commuting in a Chinese city. Int. J. Environ. Res. Publ. Health 16 (14). https://doi.org/10.3390/ijerph16142539.
Liu, G., Krishnamurthy, S., van Wesemael, P., 2021. Conceptualizing cycling experience in urban design research: a systematic literature review. Appl. Mobilities 6 (1), 92–108. https://doi.org/10.1080/23800127.2018.1494347.
Ma, J., Rao, J., Kwan, M.-P., Chai, Y., 2020a. Examining the Effects of Mobility-Based Air and Noise Pollution on Activity Satisfaction, 89. Transportation Research Part D: Transport and Environment. https://doi.org/10.1016/j.trd.2020.102633.
Ma, J., Tao, Y., Kwan, M.-P., Chai, Y., 2020b. Assessing mobility-based real-time air pollution exposure in space and time using smart sensors and GPS trajectories in Beijing. Ann. Assoc. Am. Geogr. 110 (2), 434–448. https://doi.org/10.1080/24694452.2019.1653752.
Marcus, G.E., 1995. Ethnography in/of the world system: the emergence of multi-sited ethnography. Annu. Rev. Anthropol. 24, 95–117.
Marquart, H., Ueberham, M., Schlink, U., 2021. Extending the dimensions of personal exposure assessment: a methodological discussion on perceived and measured noise and air pollution in traffic. J. Transport Geogr. 93, 103085. https://doi.org/10.1016/j.jtrangeo.2021.103085.
Matz, C.J., Stieb, D.M., Egyed, M., Brion, O., Johnson, M., 2018. Evaluation of daily time spent in transportation and traffic-influenced microenvironments by urban Canadians. Air Qual. Atmos Health 11 (2), 209–220. https://doi.org/10.1007/s11869-017-0532-6.
McArthur, D.P., Hong, J., 2019. Visualising where commuting cyclists travel using crowdsourced data. J. Transport Geogr. 74, 233–241. https://doi.org/10.1016/j.jtrangeo.2018.11.018.
Mokhtarian, P.L., 2018. Subjective well-being and travel: retrospect and prospect. Transportation. https://doi.org/10.1007/s11116-018-9935-y.
Mouratidis, K., Ettema, D., Næss, P., 2019. Urban form, travel behavior, and travel satisfaction. Transport. Res. Pol. Pract. 129, 306–320. https://doi.org/10.1016/j.tra.2019.09.002.
Murphy, E., King, E.A., 2014. Chapter 3 - environmental noise and health. In: Murphy, E., King, E.A. (Eds.), Environmental Noise Pollution. Elsevier, Boston, pp. 51–80.
Mytton, O.T., Panter, J., Ogilvie, D., 2016. Longitudinal associations of active commuting with wellbeing and sickness absence. Prev. Med. 84, 19–26. https://doi.org/10.1016/j.ypmed.2015.12.010.
Nieuwenhuijsen, M.J., 2016. Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. Environ. Health 15 (Suppl. 1), 38. https://doi.org/10.1186/s12940-016-0108-1.
Nieuwenhuijsen, M., Khreis, H., 2019. Urban and transport planning, environment and health. In: Nieuwenhuijsen, M., Khreis, H. (Eds.), Integrating Human Health into Urban and Transport Planning: A Framework. Springer International Publishing, Cham, pp. 3–16.
Nikolopoulou, M., Kleissl, J., Linden, P.F., Lykoudis, S., 2011. Pedestrians' perception of environmental stimuli through field surveys: focus on particulate pollution. Sci. Total Environ. 409 (13), 2493–2502. https://doi.org/10.1016/j.scitotenv.2011.02.002.
Noel, C., Vanroelen, C., Gadeyne, S., 2021. Qualitative research about public health risk perceptions on ambient air pollution. A review study. SSM Popul. Health 15, 100879. https://doi.org/10.1016/j.ssmph.2021.100879.
Nordbakke, S., Schwanen, T., 2013. Well-being and mobility: a theoretical framework and literature review focusing on older people. Mobilities 9 (1), 104–129. https://doi.org/10.1080/17450101.2013.784542.
Nuyts, V., Nawrot, T.S., Scheers, H., Nemery, B., Casas, L., 2019. Air pollution and self-perceived stress and mood: a one-year panel study of healthy elderly persons. Environ. Res. 177, 108644. https://doi.org/10.1016/j.envres.2019.108644.
Okokon, E.O., Turunen, A.W., Ung-Lanki, S., Vartiainen, A.-K., Tiittanen, P., Lanki, T., 2015. Road-traffic noise: annoyance, risk perception, and noise sensitivity in the Finnish adult population. Int. J. Environ. Res. Publ. Health 12 (6), 5712–5734. https://doi.org/10.3390/ijerph120605712.
Okokon, E.O., Yli-Tuomi, T., Turunen, A.W., Taimisto, P., Pennanen, A., Vouitsis, I., Lanki, T., 2017. Particulates and noise exposure during bicycle, bus and car commuting: a study in three European cities. Environ. Res. 154, 181–189. https://doi.org/10.1016/j.envres.2016.12.012.
Oltra, C., Sala, R., Boso, À., Asensio, S.L., 2017. Public engagement on urban air pollution: an exploratory study of two interventions. Environ. Monit. Assess. 189 (6), 296. https://doi.org/10.1007/s10661-017-6011-6.
Ouis, D., 2001. Annoyance from road traffic noise: a review. J. Environ. Psychol. 21 (1), 101–120. https://doi.org/10.1006/jevp.2000.0187.
Park, Y.M., 2020. Assessing personal exposure to traffic-related air pollution using individual travel-activity diary data and an on-road source air dispersion model. Health Place 63, 102351. https://doi.org/10.1016/j.healthplace.2020.102351.
Pink, S., 2015. Doing sensory ethnography/Sarah Pink. In: Los Angeles, Calif. [u.a., 2. ed. Sage Publ, Los Angeles, Calif. [u.a.
Poom, A., Willberg, E., Toivonen, T., 2021. Environmental exposure during travel: a research review and suggestions forward. Health Place 70, 102584. https://doi.org/10.1016/j.healthplace.2021.102584.
Reardon, L., Abdallah, S., 2013. Well-being and transport: taking stock and looking forward. Transport Rev. 33 (6), 634–657. https://doi.org/10.1080/01441647.2013.837117.
Roberts, H., Helbich, M., 2021. Multiple environmental exposures along daily mobility paths and depressive symptoms: a smartphone-based tracking study. Environ. Int. 156, 106635. https://doi.org/10.1016/j.envint.2021.106635.
Rojas-Rueda, D., de Nazelle, A., Tainio, M., Nieuwenhuijsen, M.J., 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ 343, d4521. https://doi.org/10.1136/bmj.d4521.
Rojas-Rueda, D., de Nazelle, A., Andersen, Z.J., Braun-Fahrländer, C., Bruha, J., Bruhova-Foltynova, H., Nieuwenhuijsen, M.J., 2016. Health impacts of active transportation in Europe. PLoS One 11 (3). https://doi.org/10.1371/journal.pone.0149990 e0149990-e0149990.
Rubik, F., 2020. Gesundheitliche Belastungen durch Umweltverschmutzung und Lärm – Ergebnisse der Umweltbewusstseinsstudien. Dessau-Rosslau. Retrieved from. https://www.umweltbundesamt.de/sites/default/files/medien/2378/dokumente/ubs-2018-factsheet-gesundheitliche_belastungen_laerm_barrierefrei.pdf.
Sass, V., Kravitz-Wirtz, N., Karceski, S.M., Hajat, A., Crowder, K., Takeuchi, D., 2017. The effects of air pollution on individual psychological distress. Health Place 48, 72–79. https://doi.org/10.1016/j.healthplace.2017.09.006.
Schlink, U., Ueberham, M., 2020. Perspectives of individual-worn sensors assessing personal environmental exposure. Engineering. https://doi.org/10.1016/j.eng.2020.07.023.
Schreckenberg, D., Guski, R., 2005. Lärmbelästigung durch Straßen- und Schienenver-kehrslärm zu unterschiedlichen Tageszeiten. Umweltmed. Forsch. Prax. 10 (2), 67–76.
Sears, C.G., Braun, J.M., Ryan, P.H., Xu, Y., Werner, E.F., Lanphear, B.P., Wellenius, G.A., 2018. The association of traffic-related air and noise pollution with maternal blood pressure and hypertensive disorders of pregnancy in the HOME study cohort. Environ. Int. 121, 574–581. https://doi.org/10.1016/j.envint.2018.09.049.
SenUVK, (n.d., SenUVK, 2021. In: Berlin Mobility Act. Senate Department for the Environment, Transport and Climate Protection, Berlin. Retrieved from. https://www.berlin.de/sen/uvk/en/traffic/transport-policy/berlin-mobility-act/. (Accessed 26 August 2021).
SenUVK, 2017. Berlin, Germany. In: Mobilität der Stadt. Berliner Verkehr in Zahlen 2017. Senate Department for the Environment, Transport and Climate Protection, Berlin (SenUVK). Retrieved from. https://www.berlin.de/sen/uvk/_assets/verkehr/verkehrsdaten/zahlen-und-fakten/mobilitaet-der-stadt-berliner-verkehr-in-zahlen-2017/mobilitaet_dt_komplett.pdf. (Accessed 26 August 2021).
Sheller, M., Urry, J., 2006. The new mobilities paradigm. Environ. Plann.: Econ. Space 38 (2), 207–226. https://doi.org/10.1068/a37268.
Stallen, P.J., 1999. A theoretical framework for environmental noise annoyance. Noise Health 1 (3), 69–79.
Stefansdottir, H., 2014. Urban routes and commuting bicyclist's aesthetic experience. FORMakademisk 7. https://doi.org/10.7577/formakademisk.777.
Strauss, A.L., Corbin, J.M., 1996. Grounded Theory : Grundlagen Qualitativer Sozialforschung. Weinheim: Weinheim. Beltz, PsychologieVerlagsUnion.

Synek, S., Koenigstorfer, J., 2019. Health effects from bicycle commuting to work: insights from participants of the German company-bicycle leasing program. J. Trans. Health 15. https://doi.org/10.1016/j.jth.2019.100619.

Szeremeta, B., Zannin, P.H.T., 2009. Analysis and evaluation of soundscapes in public parks through interviews and measurement of noise. Sci. Total Environ. 407 (24), 6143–6149. https://doi.org/10.1016/j.scitotenv.2009.08.039.

Tomsho, K.S., Schollaert, C., Aguilar, T., Bongiovanni, R., Alvarez, M., Scammell, M.K., Adamkiewicz, G., 2019. A mixed methods evaluation of sharing air pollution results with study participants via report-back communication. Int. J. Environ. Res. Publ. Health 16 (21). https://doi.org/10.3390/ijerph16214183.

Twohig-Bennett, C., Jones, A., 2018. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. Environ. Res. 166, 628–637. https://doi.org/10.1016/j.envres.2018.06.030.

Ueberham, M., Schlink, U., 2018. Wearable sensors for multifactorial personal exposure measurements – a ranking study. Environ. Int. 121, 130–138. https://doi.org/10.1016/j.envint.2018.08.057.

Ueberham, M., Schmidt, F., Schlink, U., 2018. Advanced smartphone-based sensing with open-source task automation. Sensors 18 (8). https://doi.org/10.3390/s18082456.

Ueberham, M., Schlink, U., Dijst, M., Weiland, U., 2019. Cyclists' multiple environmental Urban exposures—comparing subjective and objective measurements. Sustainability 11 (5). https://doi.org/10.3390/su11051412.

van Duppen, J., Spierings, B., 2013. Retracing trajectories: the embodied experience of cycling, urban sensescapes and the commute between 'neighbourhood' and 'city' in Utrecht, NL. J. Transport Geogr. 30, 234–243. https://doi.org/10.1016/j.jtrangeo.2013.02.006.

Van Dyck, D., Cerin, E., Conway, T.L., De Bourdeaudhuij, I., Owen, N., Kerr, J., Sallis, J.F., 2012. Perceived neighborhood environmental attributes associated with adults' transport-related walking and cycling: findings from the USA, Australia and Belgium. Int. J. Behav. Nutr. Phys. Activ. 9 (1), 70. https://doi.org/10.1186/1479-5868-9-70.

van Kempen, E., Babisch, W., 2012. The quantitative relationship between road traffic noise and hypertension: a meta-analysis. J. Hypertens. 30 (6), 1075–1086. https://doi.org/10.1097/HJH.0b013e328352ac54.

van Wee, B., Ettema, D., 2016. Travel behaviour and health: a conceptual model and research agenda. J. Trans. Health 3 (3), 240–248. https://doi.org/10.1016/j.jth.2016.07.003.

Verbeek, T., 2018. The relation between objective and subjective exposure to traffic noise around two suburban highway viaducts in Ghent: lessons for urban environmental policy. Local Environ. 23 (4), 448–467. https://doi.org/10.1080/13549839.2018.1428791.

Vich, G., Marquet, O., Miralles-Guasch, C., 2019. Green streetscape and walking: exploring active mobility patterns in dense and compact cities. J. Trans. Health 12, 50–59. https://doi.org/10.1016/j.jth.2018.11.003.

Wahlgren, L., Schantz, P., 2012. Exploring bikeability in a metropolitan setting: stimulating and hindering factors in commuting route environments. BMC Publ. Health 12 (1), 168. https://doi.org/10.1186/1471-2458-12-168.

WHO, 2018. Environmental Noise Guidlines for the European Region. World Health Organization, 9789289053563. http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2018/environmental-noise-guidelines-for-the-european-region-2018. (Accessed 30 August 2021).

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B.G., Ashiru, O., Banister, D., Roberts, I., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet 374 (9705), 1930–1943. https://doi.org/10.1016/s0140-6736(09)61714-1.

Xue, T., Zhu, T., Zheng, Y., Zhang, Q., 2019. Declines in mental health associated with air pollution and temperature variability in China. Nat. Commun. 10 (1), 2165. https://doi.org/10.1038/s41467-019-10196-y.

4.4 Article IV: Informing about the invisible – Communicating en route air pollution and noise exposure to cyclists and pedestrians using focus groups

The final Article IV draws attention to information and communication options. Referring to the findings from Article I-III, the following Article IV presents the findings from the three focus groups (see section 3.5). The participants of the focus groups are the same participants who have taken part in the go- and ride-alongs. Article IV addresses research questions Q3 and examines possibilities to inform about a healthy (air pollution and noise) and pleasant commute on daily (inevitable) routes in the city. Article IV shows that the interviewed cyclists and pedestrians had an increased awareness regarding air and noise pollution following the go- and ride-alongs and this awareness also impacted mobility practices and perceptions. The article discusses which factors should be communicated to cyclists and pedestrians to support healthy and pleasant mobility, and draws attention to possible information channels, e.g. mobility apps. Moreover, Article IV discusses if information provision about exposure on daily (inevitable) routes is a worthwhile strategy to support healthy and pleasant mobility.

Ultimately, Article IV gives a comprehensive overview of how cyclists and pedestrians want to be informed, what effects exposure information has on their perceived health, wellbeing and practices and presents new research directions. Therefore, Article IV sums up the thesis, refers back to Article I and at the same time deeply acknowledges and incorporates the findings from Article II and III.

Article IV (Preprint)

Informing about the invisible – Communicating en route air pollution and noise exposure to cyclists and pedestrians using focus groups

Heike Marquart[a,b*]

[a] Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany

[b] Geography Department, Humboldt University Berlin, Berlin, Germany

* Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

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Heike Marquart[a,b*]

[a] Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany

[b] Geography Department, Humboldt University Berlin, Berlin, Germany

* Correspondence: heike.marquart@dlr.de; Tel.: +49-30-67055-8003

Abstract

Active mobility and public transport are considered beneficial for health and wellbeing and valuable for climate change mitigation. However, cyclists and pedestrians have high air pollution and noise exposure alongside traffic, which adversely impact health and wellbeing. The measured exposure can differ from the perceived exposure, hence, communicating en route exposure is crucial. Therefore, this study investigates how to communicate route-based exposure to cyclists and pedestrians and explores if exposure communication, e.g. via smartphones, is worthwhile for healthy and pleasant commute. It is investigated how exposure feedback influences the motivation to protect oneself and how exposure information should be designed. Three focus groups with 20 cyclists/pedestrians living in Berlin, Germany, were conducted. Based on Protection Motivation Theory and Environmental Health Literacy concept, (1) experiences and practices after recognizing exposure were discussed and (2) information needs and communication strategies were developed. The results reveal a feeling of helplessness regarding the ubiquity and uncertainty of pollution and a heightened threat appraisal. Anger, anxiety and rejection were stated. Making sense of pollution levels and protective alternatives were central. A healthy routing app, including also pleasant route factors, was desired. However, information provision was also denied. Participants argued the responsibility should not be left to the commuters and planning for exposed road users would be crucial. Information provision may not be worthwhile if planning authorities do not provide healthy alternatives. People-centered approaches for tackling air pollution and noise exposure en route should be investigated further.

Keywords

Air pollution; Noise pollution; Personal Exposure; Feedback; Information; Environmental Health Literacy

1. Introduction

Ambient air pollution and noise pollution are two of the leading environmental health risk factors in urban areas, also in Europe [1-3]. Air pollution can cause respiratory diseases or cardiovascular diseases, psychological distress and impact wellbeing [3-7]. Particulate matter, specifically PM2.5, is considered responsible for a high number of premature deaths every year in Europe [3] and is the fifth-ranking mortality risk factor globally [8]. Noise exposure can lead to annoyance, psychological stress and impacts physical health [2]. A major source of air pollution and noise pollution in cities is motorized road and rail traffic [9]. Traffic related air pollution and noise pollution is high in the urban core alongside road- and rail-traffic with high traffic volume and might be even reinforced by low air exchange [10, 11]. Cyclists and pedestrians, who move alongside road- and rail-traffic, are exposed to air pollution and noise pollution higher than when separated from motorized traffic [12]. Some studies estimate they inhale higher doses of air pollution than motorized transport commuters [13, 14]. Likewise, underground subway users are exposed to higher levels of particulate matter (PM2.5) than above ground [15]. The noise level that cyclists, pedestrians or public transport users are exposed to is frequently higher than of car users [10, 16].

Even though exposure and health impacts are evident, recent studies show that cyclists and pedestrians do not perceive their exposure as it is measured by sensors [17-19] and do not see them as an impediment to walk or cycle [20]. For example, a study in Leipzig, Germany, showed that over 80% of the surveyed cyclists underestimated their exposure to particulate matter and noise pollution [19]. When people are exposed to noise over a longer period of time they adapt to it and the annoyance decreases [21]. A recent review shows that in most studies perceived and measured pollution (not only in traffic) match, however, in other studies they do not correlate [22]. Hence, this study investigates reasons behind the mismatch in perceived and measured exposure whilst moving, explores how people experience air pollution and noise exposure and discusses if communication about exposure en route is needed. Specifically, if information about protective actions and healthier routes is increasing the recognition of own exposure and helpful for a pleasant commute. The aim of this study is to identify how to communicate route-based exposure to cyclists and pedestrians and discuss if exposure communication is worthwhile for supporting a healthy and pleasant commute in the city.

Many studies which provide air pollution or noise exposure feedback measured the pollution indoor using stationary measurement devices, only few measured and gave feedback on exposure outdoor and even less measured on-the-move and gave exposure feedback [23]. Specifically, studies measuring, reporting back and investigating perceived exposure of cyclists and pedestrians are rare (see literature review of [22, 23]). The few studies to date which provide cyclists or pedestrians with air pollution and related health information emphasize the potential of exposure communication for motivating users to take less polluted routes [24, 25]. However, recent literature reviews show both, successful outcomes (empowerment, protective practices, measurably lower pollution), but also identify resignation or helplessness as a result of exposure communication [23, 26]. For example, in some studies participants report sadness, fear or disappointment when receiving exposure feedback, in others interest and surprise [23]. Generally, it is not only about the form of the feedback, but about the pollution source and the feasibility to undertake protective practices [23]. Hence, it is important to research people's needs and their coping ability when designing exposure communication and involve them in the development process. As shown by Riley et al. [26], few studies have included the public when developing exposure communication. Even less studies have involved cyclists and pedestrians. This study addresses this research gap by applying qualitative methods, specifically addressing commuters' requirements, perceptions and practices. Focus groups were set up to understand if and how cyclists and pedestrians (also on their way to public transport) want to be informed about their exposure on commuting routes. Moreover, their exposure perceptions and protective practices were explored. Following a previous study in which participants engaged with air pollution and noise exposure on-the-move and simultaneously their exposure en route was measured [17], this study addresses three research questions:

Q1. In how far does a raised awareness regarding air pollution and noise exposure on commuting routes motivate people to protect themselves?

Q2. How can information on air pollution and noise pollution be designed to support healthy and pleasant mobility in urban areas?

Q3. Is information provision about exposure on daily (inevitable) routes a worthwhile strategy to support healthy and pleasant mobility?

In section 2, the theoretical background is outlined. Section 3 presents the focus groups and the research design. In section 4 the results are presented, specifically, participants' motivation to protect themselves and their information preferences. This study specifically considers commuting routes, i.e., inevitable routes in the city for everyday purposes, and does not draw attention to leisure travel. In section 5 and 6 the findings will be discussed and conclusions drawn.

2. Theoretical background

Air pollution is a risk with a semantic pattern of perception, which it is hard to perceive: there is a complex cause-effect-relation and people need to consult information from third parties [27]. It is comparable to the risks perceived when smoking cigarettes: the invisibility of the threats and of long-term effects are similar to the invisible and long-term effects of air pollution [28]. Many studies on air pollution perception found a direct association between measurable air pollution and air pollution perception, only few studies did not find a correlation; however, from the studies which did not find a correlation, two referred to air pollution in or alongside traffic [22]. Hence, further investigating air pollution perception en route seems crucial. Studies on measurable noise pollution and perceived noise pollution found that high sound levels are not necessarily perceived as noise [19, 29, 30]. Generally, environmental health risks are more likely to be perceived by people if they are able to sense them [31]. The visual appearance of dust, the irritation to the eyes, nose or throat or the smell of exhaust fumes reinforce perception [31, 32].

2.1 Protection Motivation Theory

Studies have shown that air and noise pollution are not always recognized as severe by people as they are measured [17, 19, 34], hence, people may not always undertake health protective practices regarding their exposure. Therefore, the question is how to inform about personal exposure and how to motivate people to develop coping strategies when moving around in the city. People do not always perceive air pollution or noise pollution as a threat, so it might be an issue of health care to motivate them to undertake protective practices. For researching how to motivate people to undertake healthier practices, the Protection Motivation Theory (PMT) [35] can be consulted. The PMT is applied for researching fear appeals and social cognitive variables which influence people's intention to undertake protective actions [38]. It is a major theory in health behaviour research and has also gained attention in environmental risk research [36, 37].

According to the PMT, a person's motivation to protect oneself is influenced by two appraisal processes: the perceived threat appraisal and the coping appraisal [35, 38]. The threat appraisal considers how people estimate their vulnerability and how severe they evaluate the impact of stressors on their health [35, 39]. As for air pollution and noise exposure on-the-move it can be defined as:

- **Perceived vulnerability**
  Perception of an individual towards her or his susceptibility to air and noise pollution, i.e., the perceived probability that air and noise pollution is harming while being on-the-move.
- **Perceived severity**
  The perceived severity of air and noise pollution.

The coping appraisal refers to the degree to which a person believes his or her action can help to avoid the threat, involving self-efficacy and response efficacy [35, 39]. For air and noise pollution on-the-move it can be defined as:

- **Self-efficacy**
  The belief that one is able to successfully enact the proposed avoidance strategies or protective actions regarding air pollution and noise pollution during commuting trips.
- **Response efficacy**
  Expectancy that everyday exposure to air and noise pollution en route can be lowered through the recommended avoidance strategies or preventive actions.

The PMT was, for example, used to design information which was given to study participants to encourage healthy practices or used to create questionnaires on risk perception related to transport and Covid-19 [40]. The PMT is a valuable theory for predicting health-promoting practices [38] or designing interventions for healthy practices, such as mitigating personal exposure towards pollutants [23]. Specifically, self-efficacy was found to strongly predict intentions to protect oneself from harm, even more than threat appraisal [36, 38]. The PMT is regarded as a valuable background for this study to understand which appraisals influence cyclists' and pedestrians' motivation to protect themselves from pollution en route. However, recent research has argued that the PMT is lacking consideration of social norms, which influence protection motivation as well [37]. For researching how to increase people's threat appraisal and coping appraisal and linking it to environmental risk research, the concept for increasing environmental health literacy (EHL) is applied. Whereas PMT focuses more on the individual protection motivation [37], the EHL also addresses the collective dimensions of environmental health risks, drawing on civic life, environmental issues and wellbeing of others [41].

2.2 Environmental health literacy

Becoming environmentally health literate can be regarded as "the fundamental capacity to understand and act upon the relationship between environmental exposure and health" (Stieb et al. [42], p. 2). Environmental exposure and hazards are often a community-wide problem which can hardly be tackled by the individual [37], thus, the concept of Environmental Health Literacy (EHL) is useful to address collective actions and civic engagement next to individual awareness [43, 44]. The concept of EHL can be used to structure information campaigns or exposure communication, for example, Johnston et al. [45] have applied the EHL for informing young people regarding their particulate matter (PM2.5) exposure, showing an increased EHL. According to Gray [43], EHL comprises three dimensions: (1) awareness and knowledge, (2) skills and self-efficacy and (3) community change. Finn and O'Fallon [44] further subdivide that into: recognition, understanding, application, analysis, evaluation and creation. In theory, the EHL enhances when a person progresses through each stage, gains knowledge and ultimately takes action [44]. The first stage encompasses the recognition and understanding that a pollutant is severe and impacts health. The EHL increases, resulting in an understanding of pollution and the capability to apply, analyse and evaluate data and ultimately, gaining skills to take action. With this increased self-efficacy people are then able to undertake health-protective actions and reduce exposure [43]. In the last step, people become capable of undertaking collective actions in reducing pollution, e.g. informing policy or becoming active in the community [43]. However, it should be noted that in order to move from one stage to the next, additional skills and knowledge are required. Also, certain competencies are needed for progressing in EHL, such as understanding feasible protective options, knowing strategies to take action or recognizing uncertainties [46]. When providing information that shall increase EHL, it should be considered that information on risks has to be beneficial for the person's aims and be of interest for him/her, only then it stimulates an engagement with the information [27]. Moreover, practical or policy knowledge often needs to be incorporated to support the progressing from one stage to another, hence, integrating views from a multidisciplinary perspective is needed to create clear and actionable content [46]. Taking the concept of EHL for communicating air pollution and noise exposure in traffic could be a valuable approach for developing exposure communication strategies.

3. Research design and methods

Qualitative research is scarce in the field of air pollution related health risk perception, yet, it offers great potential to gain in-depth understandings of air pollution perception and health patterns [47]. Hence, focus groups as a qualitative research method were chosen for this study. They are part of a broader research undertaken by Marquart et al. [17], comprising three phases. This article focuses on the third phase. The first two phases are individual studies but simultaneously served as preparations for the third phase, the focus groups. In the *first phase* "go- and ride-alongs" (qualitative interviews on-the-move) with cyclists and pedestrians in Berlin, Germany, were conducted and complemented by wearable sensors [17]. In this phase the participants were accompanied by an interviewer and asked about their perceived exposure and made aware of air pollution and noise pollution en route, applying a semi-structured interview guideline (see [16]). Meanwhile, particulate matter and noise levels were measured on-the-move using DylosLogger 1700 (particle number count) and a smartphone with external microphone, GPS and sensing application, based on Ueberham et al. [18] and described in [16, 17]. The particulate matter variations in numbers could be seen on the DylosLogger 1700 screen and could be discussed with the participants whilst on-the-move. The en route measurements were presented to the participants during the focus groups. In a *second phase* the same participants were asked to track their commuting routes individually on 3-5 days[28] and complete a questionnaire about perceived exposure after each route taken using a tracking app (DLR MovingLab[29]). This aimed at increasing awareness regarding air and noise pollution on commuting routes and make the participants reflect on route choices. This served as a basis for the focus groups, which were done in a *third phase* and are subject of this article.

3.1 Focus group approach

Focus groups are interactive discussions with a predetermined group of people who have shared experiences about a certain topic [48]. It is a valuable approach to allow the participants to create new solutions of a problem, discuss perceptions and opinions regarding a shared experience and create new ideas [48, 49]. The focus group approach is considered as valuable, because all participants shared experiences made during the go- and ride-alongs, the GPS tracking and their exposure en route was measured.

The recruitment took place via social media, newsletters, flyers, but also direct contact with offices in the city centre and online neighbourhood networks. This ensured that people with different life circumstances, educational background and commuting routes could be reached. As an incentive, participants were offered personal feedback on air and noise pollution. In total, 20 people participated in three focus groups, six till eight participants each. These 20 participants are out of the greater sample who had taken part in the first two phase. Two focus groups were held on-site, one online[30]. The focus group discussions took between 1h 25m and 1h 41m. An overview of the participants can be found in Appendix A.

3.2 Procedure

The focus groups were held by a trained moderator using a semi-structured interview guideline, which comprised the following topics:

Shared experiences: Stimulating questions were asked underpinned by stimulus materials (pictures from the go- and ride-alongs, GPS-tracked routes of the individual GPS-tracking and

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[28] Due to the outbreak of the Corona pandemic in early 2020, two groups did not commute daily to work anymore and hence, did not track their routes on five days.

[29] www.movinglab.dlr.de

[30] Due to the Corona pandemic in late 2020, the third focus group was held online in November 2020 and the second focus group was in a hybrid format with two participants participating online and the others on-site (September 2020). The first focus group took place before the Corona pandemic in December 2019.

a pollution perception ranking exercise). This should encourage an exchange and discussions about experiences and perceptions of air pollution and noise pollution (or other factors) en route. The questions specifically referred to the experiences made during to the go- and ride-alongs.

Feedback/Knowledge: Participants received feedback about their exposure during the go- and ride-alongs and also in the focus groups (brochure with measurement data), including measured exposure en route (text-based explanation of high exposure and low exposure situations, a map and graph with spatial variations) and information on feasible protective actions, text-based information about adverse health impacts and information channels such as WHO or Environmental Agencies (see Annex B). Providing study participants with their monitored environmental exposure data enhances individual and community empowerment, can motivate to reduce or avoid exposure and improve environmental health literacy [50].

Information: Examples (pictures) of information sources, e.g. displays in the city or mobility apps, were presented, fuelling a discussion about how air and noise pollution could be communicated. It was emphasized, that participants could creatively develop new and innovative ideas.

3.3 Data analysis

All three focus groups were recorded and transcribed. For analysis a thematic coding was applied. This was done in an inductive-deductive approach to generate themes which are closely linked to literature and theory but still open to explore new and unforeseen topics [49, 51]. The program MAXQDA 2020 (version 20.4.1) for qualitative data analysis was used.

The analysis resulted in two themes developed deductively beforehand: (1) Protection Motivation and (2) Information source and communication of risks. The categories of theme (1) were built deductively based on PMT, consisting of: (a) perceived vulnerability and (b) perceived severity of risks as well as statements regarding (c) self-efficacy and (d) response efficacy. Theme (2) followed deductively the concept of EHL, with the following categories: (a) information that support recognition and understanding, (b) information that support application, analysis and evaluation and (c) information that support creation and community change. During the focus groups another topic appeared, which was added later: (d) information denial. The categories were developed deductively based on the theory, the codes were then developed in a deductive-inductive approach out of the data (see section 4). The transcripts were coded in two iterative rounds of coding.

4. Results

The focus groups revealed that engaging with information about air and noise pollution en route as well as being made aware of one's own exposure, as done during the go-/ride-alongs [16, 17], raised awareness. Participants' perceived vulnerability and severity of risks and their motivation to protect themselves were enhanced. However, some factors lowered their perceived effectiveness of and ability to undertake protective actions: feeling powerless, the uncertainty and ubiquity of air and noise pollution and the importance of other factors for route choices (section 4.1). The participants generated ideas for exposure communication, e.g. a healthy routing app, and demanded more community engagement. Some participants also denied receiving information on air and noise pollution, because they felt that the risk is too ubiquitous, indeterminate or it did not seem possible to protect themselves (section 4.2).

4.1 Risk perception and motivation to protect oneself

The engagement with data about personal exposure en route as well as the discussions about exposure during the go- and ride-alongs affected the perceived personal vulnerability and severity of air pollution and noise pollution. Also, a perceived low self-efficacy and a perceived low efficiency of protective actions were detected.

4.1.1 Perceived vulnerability and severity of risks

Participants are now more sensitive to air pollution and noise pollution from road or rail traffic. Engaging with their own personal exposure increased the perceived personal vulnerability on everyday routes. One participant thought the traffic situation or feeling unsafe were the source of her stress, whereas the interview made her realize that pollution smell and noise impact her wellbeing. The participants became confident in trusting own perceptions, if it was in line with the measurements. One participant started evaluating her exposure in other transport modes. Some participants described themselves as sensitive about pollution smells or noise and had felt vulnerable before, so the measurements underlined previous perceptions. However, being made aware of air pollution smells and sounds from traffic was not always reported as positive, some participants regretted they became alert:

> *"One thing that has definitely increased is my awareness for air pollution. You have made me aware of the fact that you can smell it. And since then I smell it everywhere! And that annoys me, well, I don't know if I'd rather not have known [laughs]."* (P16[31])
>
> *"My biggest eye-opener […] is that you have pushed me at some point: 'how is it regarding the noise here?' and only then I'm so much triggered to pay attention to the noise, which didn't bother me at all before, and now it bothers me extremely. This is really negative. But the big worry is that there are more of these environmental influences […] saying, 'oh yeah, probably something like that has been stressing me out all along, only I've never been able to say […] what it is'."* (P2)

Reporting back exposure can result in an increased risk awareness and increases perceived vulnerability, which may be a negative outcome from the participants view: Exposure feedback can draw attention to stressors that people were not previously aware of. This led to the fear that there are even more stressors of which one is unaware (as shown in the quote).

Participants reported that they learned that sometimes side roads with less air exchange had higher particulate matter levels than main roads with good air flow or how the number of particles varied depending on mode (car vs. bus), time (high pollution in evening hours) or distance to emitter. Altogether, participants reported increased knowledge. However, environments that were perceived to be healthy sometimes turned out to have high pollution

[31] P# refers to „Participant 'number'" (see Annex). Note that all interview statements in the paper are translated by the author from German to English.

levels, resulting in anxiousness and uncertainties: for example, greenspaces or subways could have higher air pollution levels, even though these areas were perceived as rather healthy. This lowers the trust in own perceptions and pollution risks. Participants with children stated they fear the severity of air pollution when cycling or walking with their child and tried to increasing the distance to emitters at traffic lights or on the street.

However, sometimes participants did not feel at risk. Some said they were used to pollution in the city, did not smell air pollution, felt that cycling increased health anyway or did not feel health impacts:

> *"I find it very difficult, for example, this question, to evaluate whether I felt a health burden. I can only say, no, I don't have a shortness of breath. That would be a health burden for me. I can't feel it. Of course, particulate matter and noise are a subliminal health burden, but at the moment I cannot define it like that."* (P8)

> *"I know about the particulate matter problems and so on, but, can I feel it? Can I measure it? Rather not. Big city."* (P13)

For these participants air pollution and noise pollution seem to be a prevailing circumstance when living in a big city. The immediate effects of air pollution and noise pollution can hardly be felt. The knowledge that there is an underlying risk has increased, however, the immediate threat is not felt.

4.1.2 Self-efficacy and response efficacy

The participants also reported how they tried out and felt (not) able to protect themselves from air pollution and noise pollution. Tab. 1 summarizes their statements.

Table 1: Summary of the statements regarding coping appraisal. The particular topics as discussed by the participants during the focus groups and examples retrieved from the focus group discussion transcripts.

Coping appraisal (deductively developed from PMT)	Topic discussed (inductively developed out of the data)	Description (examples)
Self-efficacy	Protective actions	▪ Increased distance to emitter ▪ Cover nose/cover ear/hold breath
	Alternative routes	▪ (Perceived) less polluted routes searched
	Alternative modes	▪ Change towards less exposed modes (bicycle instead of subway)
	Emotion focused coping	▪ Exposure is (mentally, in a psychological sense) suppressed to protect oneself
	Feeling powerless	▪ Changing mobility practices is difficult ▪ Changing routes does not have desired effect (cf. response efficacy)
	Resignation / Prioritizing	▪ Protective actions contradict with more important factors (e.g. safety, aesthetics, time, directness)

Response efficacy	Perceived health and wellbeing improve	▪ Using headphones with calm music suppresses exposure ▪ Covering nose leads to a healthier feeling ▪ Changing mode is good for "body and soul"
	Refuse (and feeling to be useless) to change route	▪ Routes are already optimized ▪ Route changes are not possible (due to built environment) ▪ Changed routes equally high exposure levels
	Importance of other factors	▪ Changed route negatively impacts other factors (time, safety, aesthetics)
	Lack of political trustworthiness	▪ Political actions demanded to improve health/wellbeing en route, instead of individuals who have to find an efficient response to stressors

Some participants tried out new routes or changed their mode from train to bicycle. Others intended to wear a mask or pulled up a scarf, hold their breath, used headphones or covered ears. A common protective practice was to increase the distance to emitters, e.g. stopping in front of traffic lights or cars with visible or smelling exhaust fumes. Some protective practices made the participants feel that they had protected their health:

> *"I've also pulled my scarf in front of my face [to lower air pollution inhalation], whether that actually helps at all? Hm… But I have the feeling that I can still breathe. [in a highly polluted area]."* (P19)

On the contrary, participants often did not believe their route change improved health and wellbeing (response efficacy) or they felt unable to undertake protective practices (self-efficacy). Recurring topics were the feeling of powerlessness or resignation. This resulted partly from unexpectedly high exposure en route, the realization of its severity or the lack of understanding local pollution patterns. This led to a lack of confidence that individual actions can improve health, because pollution was perceived as ubiquitous. The resulting feeling of powerlessness was often associated with a lack of political trustworthiness:

> *"But I do worry about what the results will be [the measurements]. Because everything changes so super slow or won't change at all at the moment. […] Maybe I have to draw consequences at some point? No, I don't want to move [walk/cycle] here anymore? Because I don't want to stress my health for the next fifteen years?"* (P2)

> *"So far, I haven't really worried about it, on purpose. I decided for myself: I live in a big city, there is particulate matter pollution, it's like that, I would be happy if it were lower, but I accept that as a marginal condition."* (P13)

The lack of confidence in planning and policy led to resignation and made people consider to move away from the city to stay healthy. Generally, suppressing exposure was a common action to deal with pollution risks on inevitable routes. Some reported resignation, since there was no other option than the polluted route:

> *"I actually looked for alternatives a long time ago and then I gave up at some point, because there were none. No better alternatives. There are alternatives, but only worse ones. Well, what I do is already what I can do and that worries me, of course. Of course, I don't want to get sick just because the politicians haven't yet realized [that the pollution is too high]. I think that's really bad…"* (P1)

> *"I checked whether I can cycle here [points at a parallel street of the main road on a map], that is parallel to the main road, so to speak. […] but these are all closed neighbourhoods, which means I ultimately end up back [on the main road] and somehow it doesn't make sense. So, I thought at this point: rather a short, intense exposition than a longer medium one."* (P6)

These quotes show that receiving information about high exposure may lead to a feeling of injustice, worries, helplessness, ignorance or acceptance, but not necessarily to an increase in self-efficacy. Some participants complained about lack of alternatives: the infrastructure often guides them along main roads with motorized traffic and perceivably less polluted residential areas were often unsuited to cycle. Moreover, routes were often optimized considering personal preferences, whereas air pollution and noise pollution were not (yet) priorities in route choices. Other factors were more decisive: time/directness, relaxing and not concentrating, quietness, aesthetic, livability or shops, excitement or safety. As a result, some participants did not want and did not feel able to change routes. Generally, most of the participants demanded a built environment which offers routes that are at the same time low polluted, pleasant and safe. One participant summarized these worries:

> *"But, the problem is, if we have no choice but to take this route, then the information is of no use to me. So, you have to get to the root [of the problem]."* (P4)

Hence, if a persons is not able to change towards a healthy route, information provision is not considered as valuable.

4.2 Information needs

The participants discussed how they want to be informed. Their statements addressed all stages of EHL, but they sometimes also refused to receive information at all. Fig. 1 provides an overview.

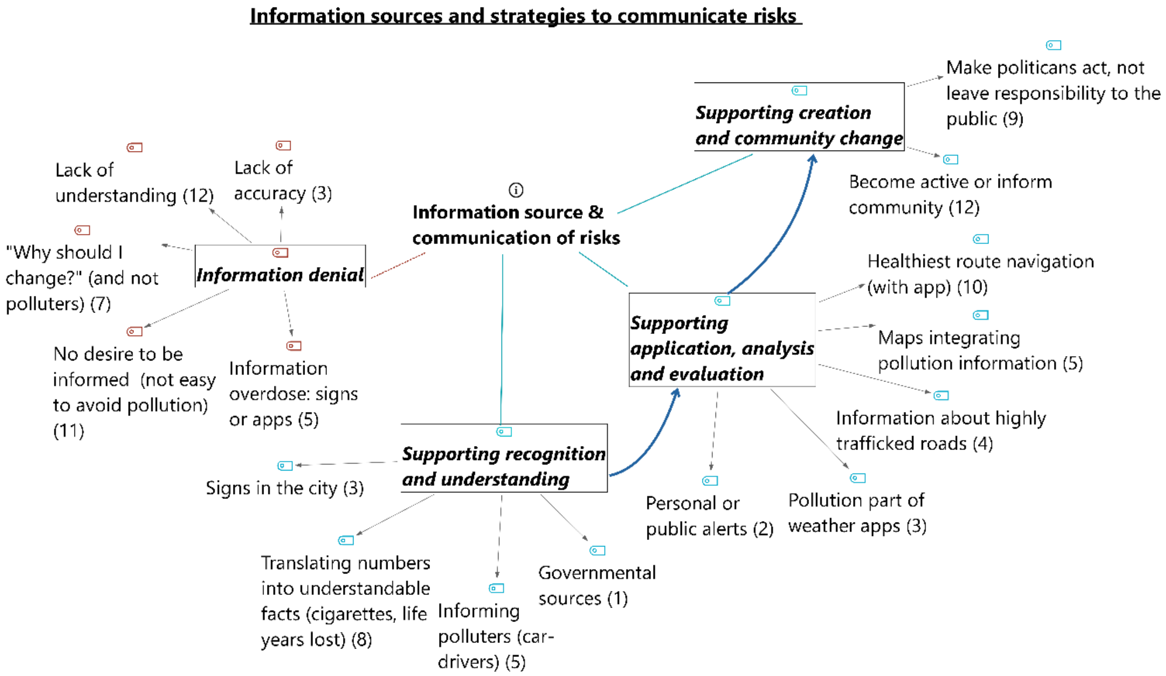


Figure 1: Overview of the codes retrieved during the thematic coding. The main codes are based on the main steps of increasing Environmental Health Literacy (blue), which built on one another. It starts with recognition and understanding, then leads to application, analysis and evaluation and ultimately results in creation and community change. The retrieved codes were allocated to the suitable EHL stage. Statements regarding information denial were coded separately (red).

4.2.1 Information supporting recognition and understanding

Information supporting recognition and understanding aims at informing people, who have not encountered with the topic yet. Participants discussed solutions such as displays in the city showing daily pollution, which was part of the focus groups' stimulus material. This would also inform polluters. Yet, it is hard to make sense of the numbers of city-wide displays. Measured exposure should be translated into something easy to understand, e.g. life years lost, comparing it to cigarettes smoked or pictures of health impacts:

> *"[…] So that you would know, hey, how many cigarettes would I smoke on my way there […] If I knew, I would smoke one versus three cigarettes on my way to work, I might decide to take another route with only one cigarette."* (P18)

Risks could also be translated into health burdens, e.g. headaches, problems with breathing/lungs or high stress levels associated with air and noise pollution exposure. This would specifically address the threat appraisal (see PMT). As discussed, however, the coping appraisals might be more influential [36, 38].

4.2.2 Information supporting application, analysis and evaluation

Healthiest route navigation was discussed the most for supporting individual mobility. Many participants desired an app that integrates current pollution levels, but also suggests alternative routes with less pollution. The "healthiest route" as an option next to, e.g. "fastest", "least cobble stones" or "most beautiful" was recommended. Participants who know the city well preferred maps with real-time air pollution and noise pollution to choose their own routes. However, as pointed out by some participants, the healthiest routing would demand for small-scale real-time pollution data. A suggestion to address this issue was an app with information on real-time information about the traffic volume on a street, which is associated with noise and air pollution.

4.2.3 Information supporting creation and community change

In the course of the focus group discussions the participants started questioning why they only talk about passively receiving information, instead of actively changing the situation. Taking part in the study and becoming aware of air and noise pollution resulted in a strong sense of activism and public engagement. The participants suggested a range of activities for the community: informing others or the public, integrating the topic in schools or adult education, supporting local initiatives, or even suing the state for not preventing health impacts. Participants also became multiplicators:

> *"I definitely walked through the neighbourhood much more consciously and also talked with many people about particulate matter pollution. And talked with my friend about why it's so dirty on our first floor, because maybe it's also dusty due to the street in front of the door and so on. So, there's a lot of things that have continued [after the interview]."* (P19)

Next to public engagement, the participants demanded political actions. Some called for more political actions to create healthy routes, instead of leaving the responsibility to search healthy routes to the cyclists and pedestrians. They concluded that they did not only want to be informed where pollution is, but get to the root of the problem and influence policy and planning

4.2.4 Information denial

During the focus groups the participants wondered why they, as the most environmentally friendly road users, should change their routes to protect themselves from pollution caused by motorized traffic ("*why should I change?*" (P10)). Less polluted routes were often perceived longer or less pleasant. Some of the participants reported anger and resignation that they have to be responsible for travelling in a healthier way by individually changing their route. Some participants feared that information provision, e.g. smartphones, might shift the focus away from the actual problem:

> *"That is interesting. That makes me think... That I automatically remain in the position of the weaker road user and say: Gosh! An app like that is great! But actually,[…] we have forgotten the main topic! Namely, the elephant in the room [idiom]. We must first take away space from the cars, […] [space], which is already allocated [to the cars]. You have to give more space to cyclists, cyclists and pedestrians."* (P9)

This resulted in information denial and refusal of receiving information. Many participants concluded they did not necessarily want to be informed. Moreover, receiving information about pollution on inevitable routes could cause stress and hence, cause health problems and lower wellbeing:

> *"Actually, I don't want to be informed about it at all, because in the end, it makes me sick. If I don't know, I have fewer problems with it."* (P15)

> *"But [I do not want information] all the time [from] displays or so, because then, I think, I will always get in a worse mood and could also… […] then it would totally piss me off and that doesn't do me any good, if I am upset about it all the time."* (P20)

Some participants reported they feel already overloaded by information, e.g. from apps or signs. Receiving additional pollution information on-the-move could increase stress, especially if the information appears when a person already rides through highly exposed areas and cannot avoid it ("*that would stress me out rather than do me any good"* (P17)). .

Finally, protecting against long-term effects of air pollution or noise pollution can contradict with the short-term desire of a comfortable, short and pleasant route. Information which is contradictory to one's own feelings and belief may lead to inaction. One participant summarized her confusion:

> *"If I perceive something as more pleasant, should I rather take this route or should I, based on the findings that we have, say: well, then I take rather the route which does not feel so good, but is actually quieter and therefore may not be a threat to my health in the long-run? Well, are there any suggestions, how we should behave? Should I rather choose according to my own perception or should I actually act according to the data?"* (P20)

These contradictions will be discussed in the following.

5. Discussion

The aim of this study was to identify how to inform cyclists and pedestrians about their noise and air pollution exposure on daily commuting routes in the city. First, communicating personal exposure to air pollution and noise pollution can empower individuals to undertake protective practices and leads to community engagement, but at the same time can also result in resignation and the feeling of powerlessness (Q1). Second, the discussion will highlight opportunities to inform about air pollution and noise pollution to support healthy and pleasant mobility (Q2), discussing that also enjoyable and pleasant route suggestions could be integrated. Finally, the question if exposure information is worthwhile to support healthy and pleasant mobility will be discussed (Q3), elaborating on participants' call for political actions and their engagement in the community.

5.1 Empowerment vs. resignation

Addressing research question Q1, receiving information on exposure increased knowledge and raised awareness: Pollution smells or traffic sounds were now perceived en route. Health impacts (e.g. headache, stress) were put in relation to the stressors. Yet, increased awareness also has its downsides.

In line with other studies, perceptions did not always match with measurements [17, 19, 29, 52] and participants partly appreciated the knowledge gain and felt confident to trust their perceptions. Reporting-back exposure measurements was regarded as positive and people are eager to receive "their" results [50, 53]; it usually increases EHL and has the potential to tackle urban air pollution [26, 43]. As for noise, research reporting back noise pollution data to the public is rather scarce [23]. People are often not aware of traffic noise and lack actions to avoid it [54, 55]. This is similar to the participants in this study. However, if people get more involved in noise pollution monitoring, they show an increasing knowledge of noise pollution in the city and a higher awareness of pleasant and unpleasant soundscapes [56]. They may be able to evaluate and integrate quieter route sections into their daily commute. Hence, participatory noise pollution monitoring has great potential to empower people and raise awareness [58, 59]. Knowing about noisy and quiet areas, such as green spaces, can decrease the perceived adverse noise pollution effects [60]. Some of the participants have already undertaken protective practices to lower noise pollution by using headphones to listen to music or podcasts (see section 4.1.2), however, this protective practice may also affect perception of sounds (e.g. cars) which act as an attentional trigger and are decisive for safe cycling or walking [57]. Some cyclists compensate that by e.g. looking around more often, using only one earbud or turning down the music [57], however, safety issues need to be considered for this protective practice. Summarizing, information on personal exposure can empower laypersons to take action and raise awareness.

Conversely, the increased awareness of a risk, which had been suppressed before, was sometimes regarded as negative. After becoming aware of smelling polluted air or hearing traffic sounds some participants felt unable to ignore it anymore. Annoyance or stress increased. Some participants wished they would never have known (section 4.1). Some air pollution studies link air pollution perceptions with (self-reported) health symptoms [22]. Perceiving odor of air pollution can lead to annoyance and trigger actual health symptoms, specifically if the odor is perceived as unpleasant [61, 62]. This is similar to noise: if a person perceives noise and feels distressed, the noise causes psychological stress, whereas the measured noise pollution itself may not significantly influence psychological stress [63]. Exposure information about stressors, which had been successfully suppressed before, can backfire and result in negative feelings, resignation and psychological stress. Nevertheless, the measurable exposure has an assessable health impact in the long term [1, 2, 7], even if it is not perceived in situ. Exposure information has therefore to be designed with caution, limiting its potential to result in psychological stress. This can be done by including information about feasible and existing protective measures.

5.2 Barriers to take action: uncertainty and ubiquity

Having feasible options to protect oneself is important. Exposure information is of no need if there are social or environmental barriers which prevent behavioral adaptations [26]. For example, built environmental factors can hinder people to take routes away from pollution or it can be the case that other factors are more decisive for route choices (e.g. safety, aesthetics, distance, time) (section 4.1.2).

A lack of understanding can also lower self-efficacy. Similar to Noel et al. [47], the link between air pollution and one's health is often shaped by uncertainty. Participants want pollution numbers to be translated into something relatable, e.g. life-years lost or cigarettes smoked (section 4.2.1). Ambient air pollution is complex and impacted by a variety of factors (e.g. wind), hence, it does not always match with people's expectations (e.g. green spaces have high pollution ("green-is-clean assumption") [64]). Presumably healthy routes are not necessarily pollution-free. This may result in doubts that healthy alternatives exist at all [65]. Relatable information is even more difficult for noise pollution on-the-move. High dB(A) levels do not necessarily represent sounds perceived as noise: the situational context, the activity performed and the transport mode impact if a sound is perceived as noise [18, 30, 63]. The reported discrepancies of measured and perceived noise on-the-move prove evidence [18, 19]. Providing real-time dB(A) measurements may not be a useful indicator, since it may not reflect actual noise annoyance. This raises the question how to lower exposure to air and noise pollution, especially if its spatial patterns are complex and the situational context decisive.

Firstly, it is recommended to prioritize planning of less polluted routes and consider other factors (aesthetics, safety, distance) when planning for cyclists and pedestrians. Only then healthy routes are an option, and information is useful. Secondly, information on air pollution and noise pollution should be relatable and address uncertainty and ubiquity, e.g. by improving real-time data with a city-wide monitoring network. Lastly, it may not be worthwhile to provide people with exposure information at this stage if they cannot change their routes. This will be elaborated in the following.

5.3 Informing about air pollution, noise pollution and pleasant routes

Exposure information should have a positive framing, trigger people emotionally, provide relevant information, communicate the co-benefits of behaviors and support undertaking the action [26]. Technical information has to be enriched with emotional triggers to be effective [46]. Studies reporting back exposure which led to protective practices exist: they included storytelling-approaches or workshops with the community next to measurement data [45, 66]. This empowered and created a feeling of ownership over the measurement campaign [45, 67]. This is similar to this study’s findings: participants felt empowered by being involved in the research process.

Several possibilities to inform commuters were identified. Information should be more than just numbers [68]. Pollution measurements could be translated into illustrations or integrated in a healthy routing app. As shown by Marquart and Schuppan [69], a healthy routing app could draw on the PMT and integrate other health-related factors, among air pollution and noise pollution. As health considerations are an important motivation for people to walk or cycle [70], a healthy routing app might be specifically interesting for cyclists and pedestrians. However, as this study has shown, a healthy routing app alone may not be worthwhile, because other decisive factors influence a pleasant commute.

As shown in this and previous research [17], sensory awareness (seeing and smelling greenery or water, aesthetics, interesting sights) and social cues can even balance negatively perceived pollution. Experiencing positive emotions and wellbeing can results in an increased physical health in general [71, 72]. Consequently, a healthy route planning app could include pleasant trip characteristics alongside pollution data. It could include social cues, such as bars and cafés, urban gardening and allotments, playgrounds or pedestrian areas, greenery and water or interesting ‘highlights’ (e.g. landmarks) along the route (see Marquart et al. [17]), next to pollution. These could be combined with factors such as directness or safety, shown to be decisive for cycling as well [70, 73]. Moreover, cyclists and pedestrians know best which factors increase their personal wellbeing along routes. With community mapping people could collectively collect knowledge, emotions and experiences of their routes and share them with peers [74]. Adding this to route planning apps could provide collective knowledge on pleasant or (hidden) less polluted routes. Exchanging subjective mobility experiences via smartphone apps can enhance the own trip experience [75]. There is no need to solely rely on general route planning apps, but include and share collective information on pleasant, less polluted routes with peers by including a community mapping approach in mobility apps.

5.4 Political actions and community engagement

Concerning Q3, the information denial stated by the participants shows that exposure information on daily (inevitable) routes may (at the moment) not be worthwhile. Some participants request that health gets a higher priority in planning decisions. This is also reflected by Ramirez et al. [68], who argues that air pollution communication concentrates too much on individual risk-fighting behavior and does not address the "structural factors" creating pollution. The increased knowledge of air pollution and noise pollution inspired some participants to raise the awareness about these stressors in their community. This is in line with other report-back studies (e.g. Tomsho et al. [76]). Facing negative environmental conditions is a motivator for environmental protest [77]. Raising awareness for air pollution and noise exposure can result in community engagement and activism [77]. Mobility apps, as the one proposed here, could integrate community mapping and communicate perceived air pollution or noise pollution to decision-makers, hence, be a valuable cornerstone for urban planning [53, 74].

5.5 Limitations

First, it should be noted that the sample may consist of an interested and rather concerned group in terms of environmental concern, who may – at least partly – be educated regarding pollution problems. As shown in previous research [78], people who feel annoyed by air pollution are usually those who are worried about it. Hence, they may participate more likely in air or noise pollution research. This rather "special interest groups", who can be dominant in participatory processes, may lead the discussions and put their interests in the focus [79, 80]. Hence, less dominant participants or other vulnerable groups, e.g. people with diseases (asthma) or children, may not participate in an extensive participatory research as this one. Future research could specifically take vulnerable populations into account [76], particularly concerning exposure in traffic, but also focus on having a diverse educated group of people when researching EHL and exposure communication. Second, taking the EHL as a framework for exposure communication can be fruitful, yet, the knowledge, skills and competencies of the targeted group need to be considered when designing exposure information. Not all people start from the same stage. Considering pre-existing knowledge, skills and competencies of the targeted group is crucial. Third, the focus groups do not give conclusions in statistical terms. The qualitative approach aims at exploring the research subject under investigation in depths and how it is constituted, rather than investigating its statistical characteristics [81]. Qualitative approaches can help to better understand environmental risk perception [37, 47] and give deep insights into how people perceive air or noise pollution, how they protect themselves and are helping to identify communication needs and planning requirements.

6. Conclusion

This article contributes to people-centered exposure communication research by exploring how cyclists and pedestrians want to be informed about a less polluted and pleasant commute. First, it was shown that providing exposure information should be centered around commuters' needs, their coping abilities and knowledge in order to avoid information denial. Addressing theories like Protection Motivation Theory (PMT) or concepts like Environmental Health Literacy (EHL) when designing information is recommended. Second, the ubiquity and uncertainty of urban air pollution and noise pollution together with the inevitability of daily commute can result in a feeling of helplessness and resignation, raising the question in how far exposure communication is worthwhile for commuting trips. Integrating air and noise pollution information in a mobility app enriched with other pleasant route aspects ("pleasant routing app") and participatory approaches is promising. Future research could develop and test an app like this, also applying quantitative methods such as surveys or GPS tracking. Ultimately, policy and planning should not leave the responsibility to the exposed road users in finding healthy routes, rather should environmentally-friendly mode users be protected against health-impacting air pollution and noise pollution by implementing planning measures. The perceived exposure, social cues and sensory awareness (greenery and water, aesthetics and interesting urban form) should receive attention in informing and planning for cyclists and pedestrians [17]. An app, which integrates pollution, pleasant route environments and addresses participatory approaches could support healthy, pleasant and pollution-free mobility in urban areas.

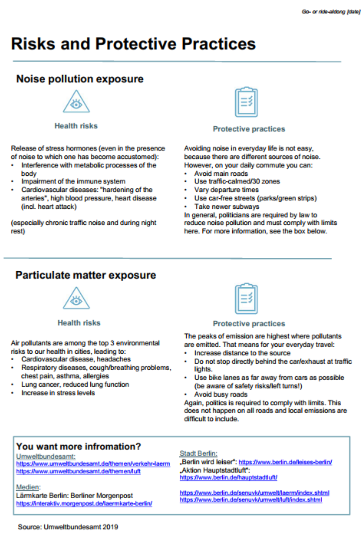
7. Appendix

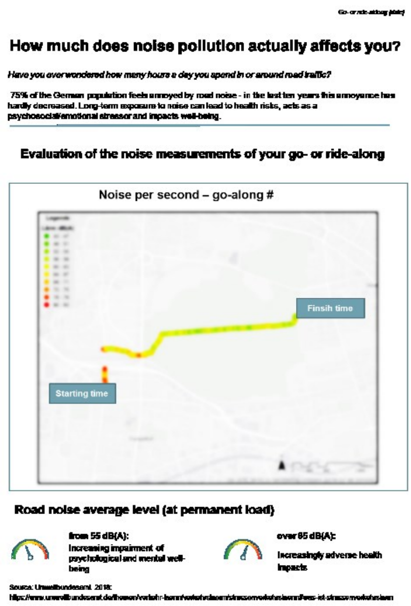
Appendix A: Overview of the participants

Partici-pant No.	Age	Female/ male	Modes of transport available	Commuting mode	Employment status
Focus group 1					
P1	55	f	Bicycle, Car-sharing, Public transport ticket	Bicycle	Full-time
P2	30	m	Car, bicycle	Bicycle	Part-time (flexible)
P3	n/a	m	Bicycle, public trasnport ticket	Bicycle	Paternity leave
P4	59	f	Bicycle, scooter sharing, public transport ticket	Walking+public transport	Self-employed
P5	25	m	Bicycle, public transport ticket	Bicycle, walking+public transport	Student
P6	24	m	Bicycle, public transport ticket	Bicycle, walking+public transport	Part-time (flexible), student
P7	42	f	Bicycle, car-sharing	Bicycle	Full-time
Focus group 2					
P8	51	f	Car, Bicycle	Bicycle	Part-time
P9	58	m	Bicycle, car-sharing, e-scooter-sharing, public transport ticket	Bicycle+public transport	Full-time
P10	50	m	Car, bicycle, public transport ticket	Bicycle, walking+public transport	Full-time

P11	51	f	Car, bicycle, car-sharing, bicycle-sharing	Bicycle	Full-time
P12	37	f	Bicycle	Bicycle	Part-time (flexible)
P13	45	m	Bicycle, Car-sharing, bike-sharing	Bicycle	Full-time
Focus group 3					
P14	28	f	Bicycle	Bicycle	Student
P15	61	m	Car, bicycle, motorbike	Bicycle	Full-time
P16	29	m	Bicycle, car-sharing, (e-)scooter-sharing, public transport ticket	Bicycle	Part-time (flexible), student
P17	31	m	Bicycle, car-sharing, bicycle-sharing	Bicycle	Part-time (flexible)
P18	31	f	Bicycle, car-sharing, public transport ticket	Bicycle	Full-time
P19	30	f	Bicycle, car-sharing, bicycle-sharing, public transport ticket	Bicycle, walking+public transport	Part-time (non-flexible), student
P20	33	f	Bicycle, car-sharing, bike-sharing, scooter-sharing	Bicycle	Part-time (flexible), self-employed

Appendix B: Example of two pages from the reporting-back brochure used as stimulus material during the focus groups: information on health impacts of exposure and potential protective practices (left) and an example of reported back noise measurements (right; translated from German to English for this article; the measurement data is made blurry for privacy reasons).





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8. Literature

1. Hänninen, O., Knol Anne, B., Jantunen, M., Lim, T.-A., Conrad, A., Rappolder, M., Carrer, P., Fanetti, A.-C., Kim, R., Buekers, J., Torfs, R., Iavarone, I., Classen, T., Hornberg, C., and Mekel Odile, C.L. (2014). Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries. *Environmental Health Perspectives*. *122*(5), 439-446. doi:10.1289/ehp.1206154.
2. WHO, (2018). *Environmental Noise Guidlines for the European Region*. 2018: World Health Organization.
3. EEA, E.E.A. (2020). Air quality in Europe – 2020 report. *Technical Report*. *9/2020*. doi:10.2800/786656.
4. Sass, V., Kravitz-Wirtz, N., Karceski, S.M., Hajat, A., Crowder, K., and Takeuchi, D. (2017). The effects of air pollution on individual psychological distress. *Health & place*. *48*, 72-79. doi:10.1016/j.healthplace.2017.09.006.
5. Li, Y., Guan, D., Tao, S., Wang, X., and He, K. (2018). A review of air pollution impact on subjective well-being: Survey versus visual psychophysics. *Journal of Cleaner Production*. *184*, 959-968. doi:10.1016/j.jclepro.2018.02.296.
6. Lin, W.-H., Pan, W.-C., and Yi, C.-C. (2019). "Happiness in the air?" the effects of air pollution on adolescent happiness. *BMC Public Health*. *19*(1), 795. doi:10.1186/s12889-019-7119-0.
7. Krzyzanowski, M., Kuna-Dibbert, B., and Schneider, J., (2005). *Health effects of transport-related air pollution* 2005: World Health Organization (WHO).
8. Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., and Forouzanfar, M.H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*. *389*(10082), 1907-1918. doi:10.1016/s0140-6736(17)30505-6.
9. EEA, E.E.A. (2020). Environmental noise in Europe — 2020. *EEA Report*. *22/2019*. doi:10.2800/686249.
10. Liu, Y., Lan, B., Shirai, J., Austin, E., Yang, C., and Seto, E. (2019). Exposures to Air Pollution and Noise from Multi-Modal Commuting in a Chinese City. *Int J Environ Res Public Health*. *16*(14). doi:10.3390/ijerph16142539.
11. Keuken, M., Sanderson, E., van Aalst, R., Borken, J., and Schneider, J.,(2005). 2. Contribution of traffic to levels of ambient air pollution in Europe. In M. Krzyzanowski, Kuna-Dibbert, B., and Schneider, J., (Ed.), *Health effects of transport-related air pollution /*). World Health Organization (WHO).
12. Mitsakou, C., Adamson, J.P., Doutsi, A., Brunt, H., Jones, S.J., Gowers, A.M., and Exley, K.S. (2021). Assessing the exposure to air pollution during transport in urban areas – Evidence review. *Journal of Transport & Health*. *21*, 101064. doi:https://doi.org/10.1016/j.jth.2021.101064.
13. Cepeda, M., Schoufour, J., Freak-Poli, R., Koolhaas, C.M., Dhana, K., Bramer, W.M., and Franco, O.H. (2017). Levels of ambient air pollution according to mode of transport: a systematic review. *The Lancet Public Health*. *2*(1), e23-e34. doi:10.1016/s2468-2667(16)30021-4.
14. Okokon, E.O., Yli-Tuomi, T., Turunen, A.W., Taimisto, P., Pennanen, A., Vouitsis, I., Samaras, Z., Voogt, M., Keuken, M., and Lanki, T. (2017). Particulates and noise

exposure during bicycle, bus and car commuting: A study in three European cities. *Environ Res*. *154*, 181-189. doi:10.1016/j.envres.2016.12.012.
15. Shakya, K.M., Saad, A., and Aharonian, A. (2020). Commuter exposure to particulate matter at underground subway stations in Philadelphia. *Building and Environment*. *186*. doi:10.1016/j.buildenv.2020.107322.
16. Yao, C., Ma, A.K., Cushing, S.L., and Lin, V.Y.W. (2017). Noise exposure while commuting in Toronto - a study of personal and public transportation in Toronto. *J Otolaryngol Head Neck Surg*. *46*(1), 62. doi:10.1186/s40463-017-0239-6.
17. Marquart, H., Stark, K., and Jarass, J. (2022). How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute. *Journal of Transport & Health*. *24*, 101325. doi:https://doi.org/10.1016/j.jth.2021.101325.
18. Marquart, H., Ueberham, M., and Schlink, U. (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. doi:https://doi.org/10.1016/j.jtrangeo.2021.103085.
19. Ueberham, M., Schlink, U., Dijst, M., and Weiland, U. (2019). Cyclists' Multiple Environmental Urban Exposures—Comparing Subjective and Objective Measurements. *Sustainability*. *11*(5). doi:10.3390/su11051412.
20. Badland, H.M. and Duncan, M.J. (2009). Perceptions of air pollution during the work-related commute by adults in Queensland, Australia. *Atmospheric Environment*. *43*(36), 5791-5795. doi:10.1016/j.atmosenv.2009.07.050.
21. Zhang, X., Zhou, S., Kwan, M.-P., Su, L., and Lu, J. (2020). Geographic Ecological Momentary Assessment (GEMA) of environmental noise annoyance: the influence of activity context and the daily acoustic environment. *International Journal of Health Geographics*. *19*(1), 50. doi:10.1186/s12942-020-00246-w.
22. Cori, L., Donzelli, G., Gorini, F., Bianchi, F., and Curzio, O. (2020). Risk Perception of Air Pollution: A Systematic Review Focused on Particulate Matter Exposure. *Int J Environ Res Public Health*. *17*(17). doi:10.3390/ijerph17176424.
23. Becker, A.M., Marquart, H., Masson, T., Helbig, C., and Schlink, U. (2021). Impacts of Personalized Sensor Feedback Regarding Exposure to Environmental Stressors. *Current Pollution Reports*. *7*(4), 579-593. doi:10.1007/s40726-021-00209-0.
24. Anowar, S., Eluru, N., and Hatzopoulou, M. (2017). Quantifying the value of a clean ride: How far would you bicycle to avoid exposure to traffic-related air pollution? *Transportation Research Part A: Policy and Practice*. *105*, 66-78. doi:10.1016/j.tra.2017.08.017.
25. Koenigstorfer, J. (2018). Active Transportation Decision-Making against the Background of Air Quality Information Provision: Walking Route Preferences of German Residents. *Urban Science*. *2*(1), 19. doi:10.3390/urbansci2010019.
26. Riley, R., de Preux, L., Capella, P., Mejia, C., Kajikawa, Y., and de Nazelle, A. (2021). How do we effectively communicate air pollution to change public attitudes and behaviours? A review. *Sustainability Science*. doi:10.1007/s11625-021-01038-2.
27. Renn, O. (2014). Risikowahrnehmung in der Bevölkerung – Implikationen für das Sicherheitsempfinden. *Zeitschrift für Außen- und Sicherheitspolitik*. *8*(1), 49-67. doi:10.1007/s12399-014-0436-6.
28. Elias, W. and Shiftan, Y. (2012). The influence of individual's risk perception and attitudes on travel behavior. *Transportation Research Part A: Policy and Practice*. *46*(8), 1241-1251. doi:https://doi.org/10.1016/j.tra.2012.05.013.
29. Verbeek, T. (2018). The relation between objective and subjective exposure to traffic noise around two suburban highway viaducts in Ghent: lessons for urban

environmental policy. *Local Environment*. *23*(4), 448-467. doi:10.1080/13549839.2018.1428791.

30. Kou, L., Kwan, M.-P., and Chai, Y. (2020). The effects of activity-related contexts on individual sound exposures: A time–geographic approach to soundscape studies. *Environment and Planning B: Urban Analytics and City Science*. *48*(7), 2073-2092. doi:10.1177/2399808320965243.
31. Gatersleben, B. and Uzzell, D. (2000). THE RISK PERCEPTION OF TRANSPORT–GENERATED AIR POLLUTION. *IATSS Research*. *24*(1), 30-38. doi:https://doi.org/10.1016/S0386-1112(14)60015-7.
32. Nikolopoulou, M., Kleissl, J., Linden, P.F., and Lykoudis, S. (2011). Pedestrians' perception of environmental stimuli through field surveys: focus on particulate pollution. *Sci Total Environ*. *409*(13), 2493-502. doi:10.1016/j.scitotenv.2011.02.002.
33. Bickerstaff, K. (2004). Risk perception research: socio-cultural perspectives on the public experience of air pollution. *Environ Int*. *30*(6), 827-40. doi:10.1016/j.envint.2003.12.001.
34. Gany, F., Bari, S., Prasad, L., Leng, J., Lee, T., Thurston, G.D., Gordon, T., Acharya, S., and Zelikoff, J.T. (2017). Perception and reality of particulate matter exposure in New York City taxi drivers. *J Expo Sci Environ Epidemiol*. *27*(2), 221-226. doi:10.1038/jes.2016.23.
35. Rogers, R.W. (1975). A Protection Motivation Theory of Fear Appeals and Attitude Change1. *The Journal of Psychology*. *91*(1), 93-114. doi:10.1080/00223980.1975.9915803.
36. Plotnikoff, R.C. and Trinh, L. (2010). Protection motivation theory: is this a worthwhile theory for physical activity promotion? *Exerc Sport Sci Rev*. *38*(2), 91-8. doi:10.1097/JES.0b013e3181d49612.
37. Heidenreich, A., Köhler, S., Seebauer, S., and Masson, T. (2020). Schutzhandeln bei Hochwasser, Hitze und Co. – Umweltpsychologische Theorien für die Naturrisikenforschung. *Umweltpsychologie*. *24*(2), 92-109.
38. Norman, P., Boer, H., and Seydel, E.R.,(2005). Protection motivation theory. In M. Conner and Norman, P., (Ed.), *Predicting Health Behaviour: Research and Practice with Social Cognition Models* pp.(81-126). Open University Press.
39. Maddux, J.E. and Rogers, R.W. (1983). Protection motivation and self-efficacy: A revised theory of fear appeals and attitude change. *Journal of Experimental Social Psychology*. *19*(5), 469-479. doi:https://doi.org/10.1016/0022-1031(83)90023-9.
40. Barbieri, D.M., Lou, B., Passavanti, M., Hui, C., Hoff, I., Lessa, D.A., Sikka, G., Chang, K., Gupta, A., Fang, K., Banerjee, A., Maharaj, B., Lam, L., Ghasemi, N., Naik, B., Wang, F., Mirhosseini, A.F., Naseri, S., Liu, Z., Qiao, Y., Tucker, A., Wijayaratna, K., Peprah, P., Adomako, S., Yu, L., Goswami, S., Chen, H., Shu, B., Hessami, A., Abbas, M., Agarwal, N., and Rashidi, T.H. (2021). Impact of COVID-19 pandemic on mobility in ten countries and associated perceived risk for all transport modes. *PLoS ONE*. *16*(2 February). doi:10.1371/journal.pone.0245886.
41. Gray, K.M. and Lindsay, M.,(2019). Measuring Environmental Health Literacy. In S. Finn and O'Fallon, L., (Ed.), *Environmental Health Literacy*. pp.(19-43). Springer: Cham.
42. Stieb, D.M., Huang, A., Hocking, R., Crouse, D.L., Osornio-Vargas, A.R., and Villeneuve, P.J. (2019). Using maps to communicate environmental exposures and health risks: Review and best-practice recommendations. *Environ Res*. *176*, 108518. doi:10.1016/j.envres.2019.05.049.
43. Gray, K.M. (2018). From Content Knowledge to Community Change: A Review of Representations of Environmental Health Literacy. *Int J Environ Res Public Health*. *15*(3). doi:10.3390/ijerph15030466.

44. Finn, S. and O'Fallon, L. (2017). The Emergence of Environmental Health Literacy-From Its Roots to Its Future Potential. *Environmental health perspectives*. *125*(4), 495-501. doi:10.1289/ehp.1409337.
45. Johnston, J.E., Juarez, Z., Navarro, S., Hernandez, A., and Gutschow, W. (2019). Youth Engaged Participatory Air Monitoring: A 'Day in the Life' in Urban Environmental Justice Communities. *Int J Environ Res Public Health*. *17*(1). doi:10.3390/ijerph17010093.
46. Hoover, A.G.,(2019). Defining Environmental Health Literacy. In S. Finn and O'Fallon, L., (Ed.), *Environmental Health Literacy*. pp.(3-18). Springer: Cham.
47. Noel, C., Vanroelen, C., and Gadeyne, S. (2021). Qualitative research about public health risk perceptions on ambient air pollution. A review study. *SSM Popul Health*. *15*, 100879. doi:10.1016/j.ssmph.2021.100879.
48. Hennink, M.M., (2014). *Focus group discussions / Monique M. Hennink*. 2014, New York, New York: New York, New York : Oxford University Press.
49. Schulz, M.,(2012). Quick and easy!? Fokusgruppen in der angewandten Sozialwissenschaft. In M. Schulz, Mack, B., and Renn, O., (Ed.), *Fokusgruppen in der empirischen Sozialwissenschaft: Von der Konzeption bis zur Auswertung*. pp.(9-22). VS Verlag für Sozialwissenschaften: Wiesbaden.
50. Brody, J.G., Dunagan, S.C., Morello-Frosch, R., Brown, P., Patton, S., and Rudel, R.A. (2014). Reporting individual results for biomonitoring and environmental exposures: lessons learned from environmental communication case studies. *Environ Health*. *13*, 40. doi:10.1186/1476-069X-13-40.
51. Kuckartz, U., (2020). *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung*. 5., überarbeitete Aufl. ed. 2020, Weinheim Beltz Verlagsgruppe: Weinheim Beltz Verlagsgruppe.
52. Johnson, B.B. (2012). Experience with urban air pollution in Paterson, New Jersey and implications for air pollution communication. *Risk Anal*. *32*(1), 39-53. doi:10.1111/j.1539-6924.2011.01669.x.
53. Mason, L., Hathaway, J., Ellis, K., and Harrison, T. (2016). Public Interest in Microclimate Data in Knoxville, Tennessee, USA. *Sustainability*. *9*(1). doi:10.3390/su9010023.
54. Szeremeta, B. and Zannin, P.H.T. (2009). Analysis and evaluation of soundscapes in public parks through interviews and measurement of noise. *Science of The Total Environment*. *407*(24), 6143-6149. doi:https://doi.org/10.1016/j.scitotenv.2009.08.039.
55. Gilani, T.A. and Mir, M.S. (2021). A study on the assessment of traffic noise induced annoyance and awareness levels about the potential health effects among residents living around a noise-sensitive area. *Environmental Science and Pollution Research*. *28*(44), 63045-63064. doi:10.1007/s11356-021-15208-3.
56. Becker, M., Caminiti, S., Fiorella, D., Francis, L., Gravino, P., Haklay, M.M., Hotho, A., Loreto, V., Mueller, J., Ricchiuti, F., Servedio, V.D., Sirbu, A., and Tria, F. (2013). Awareness and learning in participatory noise sensing. *PLoS One*. *8*(12), e81638. doi:10.1371/journal.pone.0081638.
57. Stelling-Konczak, A., van Wee, G.P., Commandeur, J.J.F., and Hagenzieker, M. (2017). Mobile phone conversations, listening to music and quiet (electric) cars: Are traffic sounds important for safe cycling? *Accident Analysis & Prevention*. *106*, 10-22. doi:https://doi.org/10.1016/j.aap.2017.05.014.
58. Maisonneuve, N., Stevens, M., and Ochab, B. (2010). Participatory noise pollution monitoring using mobile phones. *Information Polity*. *15*(1,2), 51-71. doi:10.3233/ip-2010-0200.

59. Picaut, J., Fortin, N., Bocher, E., Petit, G., Aumond, P., and Guillaume, G. (2019). An open-science crowdsourcing approach for producing community noise maps using smartphones. *Building and Environment*. *148*, 20-33. doi:https://doi.org/10.1016/j.buildenv.2018.10.049.
60. van Kamp, I., Klaeboe, R., Brown, L., and Lercher, P.,(2016). Soundscapes, Human Restoration, and Quality of Life In J. Kang and Schulte-Fortkamp, B., (Ed.), *Soundscape and the Built Environment*). CRC Press: Boca Raton.
61. Orru, K., Nordin, S., Harzia, H., and Orru, H. (2018). The role of perceived air pollution and health risk perception in health symptoms and disease: a population-based study combined with modelled levels of PM10. *International Archives of Occupational and Environmental Health*. *91*(5), 581-589. doi:10.1007/s00420-018-1303-x.
62. Claeson, A.S., Liden, E., Nordin, M., and Nordin, S. (2013). The role of perceived pollution and health risk perception in annoyance and health symptoms: a population-based study of odorous air pollution. *Int Arch Occup Environ Health*. *86*(3), 367-74. doi:10.1007/s00420-012-0770-8.
63. Kou, L., Tao, Y., Kwan, M.-P., and Chai, Y. (2020). Understanding the relationships among individual-based momentary measured noise, perceived noise, and psychological stress: A geographic ecological momentary assessment (GEMA) approach. *Health & Place*. *64*, 102285. doi:https://doi.org/10.1016/j.healthplace.2020.102285.
64. Heydon, J. and Chakraborty, R. (2020). Can portable air quality monitors protect children from air pollution on the school run? An exploratory study. *Environmental Monitoring and Assessment*. *192*(3), 195. doi:10.1007/s10661-020-8153-1.
65. Oltra, C., Sala, R., Boso, À., and Asensio, S.L. (2017). Public engagement on urban air pollution: an exploratory study of two interventions. *Environmental Monitoring and Assessment*. *189*(6), 296. doi:10.1007/s10661-017-6011-6.
66. Varaden, D., McKevitt, C., and Barratt, B. (2018). Making the invisible visible: Engaging school children in monitoring air pollution in London. *Research for All*. *2*(2), 267-288. doi:10.18546/rfa.02.2.06.
67. Mahajan, S., Kumar, P., Pinto, J.A., Riccetti, A., Schaaf, K., Camprodon, G., Smári, V., Passani, A., and Forino, G. (2020). A citizen science approach for enhancing public understanding of air pollution. *Sustainable Cities and Society*. *52*. doi:10.1016/j.scs.2019.101800.
68. Ramirez, A.S., Ramondt, S., Van Bogart, K., and Perez-Zuniga, R. (2019). Public Awareness of Air Pollution and Health Threats: Challenges and Opportunities for Communication Strategies To Improve Environmental Health Literacy. *J Health Commun*. *24*(1), 75-83. doi:10.1080/10810730.2019.1574320.
69. Marquart, H. and Schuppan, J. (2022). Promoting Sustainable Mobility: To What Extent Is “Health” Considered by Mobility App Studies? A Review and a Conceptual Framework. *14*(1), 47.
70. Ek, K., Wårell, L., and Andersson, L. (2021). Motives for walking and cycling when commuting – differences in local contexts and attitudes. *European Transport Research Review*. *13*(1). doi:https://doi.org/10.1186/s12544-021-00502-5.
71. Steptoe, A., Deaton, A., and Stone, A.A. (2015). Subjective wellbeing, health, and ageing. *The Lancet*. *385*(9968), 640-648. doi:10.1016/S0140-6736(13)61489-0.
72. Lyubomirsky, S., King, L., and Diener, E. (2005). The benefits of frequent positive affect: does happiness lead to success? *Psychol Bull*. *131*(6), 803-55. doi:10.1037/0033-2909.131.6.803.

73. Hardinghaus, M. and Nieland, S. (2021). Assessing cyclists' routing preferences by analyzing extensive user setting data from a bike-routing engine. *European Transport Research Review*. *13*(1). doi:10.1186/s12544-021-00499-x.
74. Pánek, J. (2019). Mapping citizens' emotions: participatory planning support system in Olomouc, Czech Republic. *Journal of Maps*. *15*(1), 8-12. doi:10.1080/17445647.2018.1546624.
75. Ross, T., Burris, A., Oliveira, L., Arnott, B., and Araujo-Soares, V.,(2015). A Feasibility Study of the Effect of Phone-Based Feedback of Other Commuters' Subjective Experiences on Driver Intentions to Change. In A. Marcus, Editor *Design, User Experience, and Usability: Design Discourse*. pp.(548-558). Springer International Publishing: Cham.
76. Tomsho, K.S., Schollaert, C., Aguilar, T., Bongiovanni, R., Alvarez, M., Scammell, M.K., and Adamkiewicz, G. (2019). A Mixed Methods Evaluation of Sharing Air Pollution Results with Study Participants via Report-Back Communication. *International Journal of Environmental Research and Public Health*. *16*(21). doi:10.3390/ijerph16214183.
77. Preisendörfer, P., Herold, L., and Kurz, K. (2020). Road Traffic and Aircraft Noise as Drivers of Environmental Protest? *KZfSS Kölner Zeitschrift für Soziologie und Sozialpsychologie*. *72*(2), 165-191. doi:10.1007/s11577-020-00686-z.
78. Machado, M., Santos, J.M., Frere, S., Chagnon, P., Reisen, V.A., Bondon, P., Ispany, M., Mavroidis, I., and Reis, N.C., Jr. (2021). Deconstruction of annoyance due to air pollution by multiple correspondence analyses. *Environ Sci Pollut Res Int*. *28*(35), 47904-47920. doi:10.1007/s11356-021-13958-8.
79. Bickerstaff, K., Tolley, R., and Walker, G. (2002). Transport planning and participation: the rhetoric and realities of public involvement. *Journal of Transport Geography*. *10*(1), 61-73. doi:https://doi.org/10.1016/S0966-6923(01)00027-8.
80. Nared, J.,(2020). Participatory transport planning: The experience of eight european metropolitan regions. In J. Nared and Bole, D., (Ed.), *Participatory Research and Planning in Practice. The Urban Book Series* pp.(13-29). Springer, Cham.
81. Lamnek, S. and Krell, C., (2016). *Qualitative Sozialforschung* 6., überarbeitete Auflage ed. 2016, Weinheim, Basel: Beltz Verlag.

5. Conclusions, implications and final remarks

This thesis explored personal exposure, perceived health, wellbeing and practices of cyclists and pedestrians on-the-move. Firstly, the applied go- and ride-along interviews complemented by wearable sensors investigated in-depths cyclists' and pedestrians' commute, including how they perceive their surroundings, but also their perceived and measured personal exposure. This approach revealed reasons behind discrepancies and similarities of pollution measurements and exposure perception (Articles II and III). Secondly, this increased awareness of the participants concerning noise and air pollution en route served as a basis for the second aim of this thesis: investigating possible communication strategies about healthy routing tailored to cyclists and pedestrians needs. The literature review showed that exposure information and other health-components are missing in mobility apps for supporting sustainable mobility choices (Article I). The focus groups (Article IV) provided in a participative manner space to discuss possibilities to inform cyclists and pedestrians about healthy and pleasant routes.

The following sections unite the findings from the four research articles of this thesis. The insights regarding perceived and measured personal exposure, situational context and sensory awareness based on Article II and III are summarized (section 5.1). Following this, section 5.2 integrates these findings into communication strategies, drawing conclusions for exposure communication based on Article I and IV (section 5.2). Thereafter, implications for research, urban and transport planning are presented (section 5.3). The study design is then reflected upon (section 5.4). The thesis concludes with an outlook for future research (section 5.5).

5.1 Main findings of the thesis: perceived and measured personal exposure, health and wellbeing en route

The findings from the go- and ride-alongs complemented by wearable sensors provide deep insights into daily commute and related exposure, perceptions and related mobility practices. Recent research has already investigated the personal exposure of cyclists and pedestrians on-the-move, i.e. integrating both the objectively measurable exposure and the subjectively perceived exposure on-the-move (see literature review in Article II). This thesis has integrated these different dimensions and further enriched them by the situational context through accompanying commuters on-the-move. Thus, extending the dimensions of personal exposure assessment (Article II). Figure 6 integrates the insights from Article II and III. It presents an overview of the researched components which influence personal exposure, health, wellbeing and practices en route. The specific components (Fig. 6) are described in Article II and Article III and will now shortly be outlined.

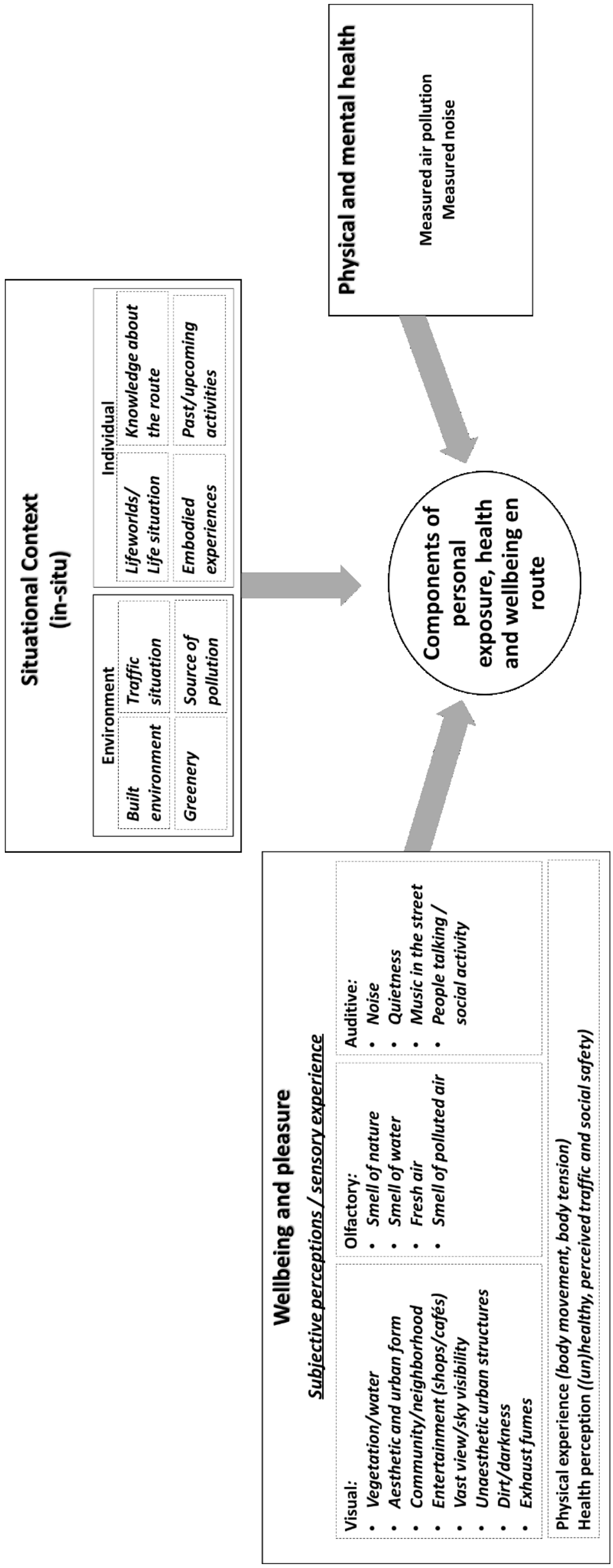

Figure 6: Components of personal exposure, health and wellbeing en route as identified in this thesis (own illustration, based on Marquart et al. (2022) and Marquart et al. (2021); Article II, III)

Article II introduced the **situational context**, showing that leaving work, being close to home, knowledge about upcoming negative route sections, past experiences of related life situations, but also environmental cues referring to the immediate environment, influence how exposure, health and wellbeing is perceived (Article II). For example, leaving work heightens the mood, hence, increases wellbeing in polluted areas. Similar with arriving home, when the neighbourhood feeling and fellow urban dwellers make the journey enjoyable, even though rather crowded streets can be measurably louder (Article II and III).

Next to the situational context, Article III explored cyclists' and pedestrians' **subjective experiences and perceptions** of built (e.g. infrastructure, green spaces, trees) and non-built (e.g. neighbourhood feeling) environmental factors. The high importance of visual, olfactory and auditive experiences en route, the importance of social cues, interesting sites, nature and the physical experience while walking or cycling is discovered. As revealed by interviewing the participants on-the-move, this influences health perception, but specifically wellbeing and commuting practices. The participants engage deeply with their environment as they move, sensing it in a variety of ways. Their sensing body and their embodied experiences during movement play an important role for pleasant commuting. The participants talked about their sensory awareness on-the-move: for example how they negatively perceive smelling polluted air, or the positive smell of water, the pleasantness when hearing subway musicians or the annoyance when being made aware of traffic sounds (Article II and III). Moreover, they emphasized the positive impact of passing fellow urban dwellers who do leisure activities, or the dislike when passing dirty, dark or unattractive areas. Cyclists' and pedestrians' evaluation of the environment is not always in line with the measurement data: they were only in line in certain circumstances (e.g. in an underpass where pollution smell was detected or traffic noise close to a freeway). It was detected that positively perceived environments can sometimes balance measurable high pollution (Article II and III). Considering these factors when planning urban space is decisive for supporting pleasant and perceived healthy commute (cf. section 5.3).

However, **measurable air pollution and noise** has a scientifically proven physiological impact on the physical and mental health of humans (e.g. Hänninen et al., 2014; Krzyzanowski et al., 2005; Mueller et al., 2017; WHO, 2018). This should not be underestimated or neglected. Moreover, commuters' visually, olfactory or auditive perceived air pollution or noise en route, even if it was not measured comparably as high as it was perceived in the particular situation, negatively influences wellbeing and perceived health (see Article III). Whereas this thesis did not further examine these measurable physical and mental health impacts, the perception of stressors can have an impact in perceived health and wellbeing. By this, the perceived exposure can actually impact physical health (Orru et al., 2018). Acknowledging that the commuting person is a sensing body, who does not solely, passively move from A to B, but who senses the environment through the body, whose sensing influences health and wellbeing and whose passing-by-environments also engenders identities is important for researching human mobility (Hein et al., 2008).

Other studies on personal exposure have as well demonstrated the importance of the situational context, embodied experiences and senses (see section 2 and Article II for a literature overview). However, this thesis has specifically linked the subjectively perceived factors influencing perceived health and wellbeing en route, the subjectively perceived and objectively detectable situational context and the actual measurable air pollution and noise of moving pedestrians and cyclists. Acknowledging the interplay of subjectively perceived and objectively measured exposure and the situational context is considered valuable for identifying planning and policy measures which can improve cycling and walking in cities. As for communicating about healthy and pleasant routes, it is not only about providing measured pollution data, but about designing information and communication strategies which take the here presented subjective components into account.

5.2 Applications of the findings: communicating en route exposure to cyclists and pedestrians

This thesis has given cyclists and pedestrians a voice in sharing their commuting experiences and their information needs regarding a healthy and pleasant commute. The following suggestions, derived from the go- and ride-alongs (Article II and III), inspired by the focus groups (Article IV) and enriched by the existing literature about health and mobility apps (Article I), will highlight possibilities to inform commuters about healthy and pleasant mobility. A pleasant routing app and other possible information options, for example via advanced mobile communication technologies (e.g. virtual or augmented reality), will be discussed.

The focus groups revealed that commuters have to balance air pollution or noise exposure information against a variety of other factors which influence their route choices (e.g. time, costs, safety, comfort, aesthetics, greenery, social aspects) (Article IV). These factors could be implemented in mobility apps, alongside air pollution and noise information or other mobility-related health components (as presented in Article I). A “pleasant routing app”, which was suggested in course of this thesis (see Article IV), could support healthy and pleasant mobility. By taking the developed conceptual framework for mobility app development (Article I), integrating decisive route factors for a pleasant and perceived healthy commute (Article II and III) and expanding it with information and communication needs of the participants (Article IV), a pleasant routing application is proposed. The proposed app could support individuals to choose a healthy, but also pleasant commute, and could integrate the following:

- **Social cues**: routes alongside cafés, bars, playgrounds, residential shops, leisure areas
- **Environmental cues**: routes alongside greenery, water, interesting sites/highlights, landmarks
- Other **mobility-related health components**: air pollution (estimated on a route), noise pollution (based on official noise action plans referring to traffic-noise), safety (e.g. numbers of traffic injuries on a route), physical activity (e.g. calories burned, kilometres cycled/walked)
- **Participatory tools**: community mapping (pinpointing) pleasurable routes or highlights along the route, locate hidden-paths or short-cuts, perceived high polluted routes
- **Health research theories**: taking health theories such as the PMT or concepts such as EHL as a guiding principle when designing a pleasant routing app

With these components, the application could address the information needs and influential route aspects that this thesis has revealed. The application of participatory tools, which can enrich the underlying map data, could additionally make the routing more consistent than relying on maps from commercial or professional mapping providers (Dobson, 2013).

As this thesis has shown, social or environmental cues en route play a key role for a pleasant and perceived healthy commute. Subjective commuting experiences, emotional attachments to places, interesting sites as well as route highlights could be shared with others through participatory tools in mobility apps or via the internet, for example, as also Pánek (2019) has argued. Having a saying in decision-making processes and sharing subjective experiences of one's route with others was desired by the participants in this thesis (Article IV). For addressing this demand, approaches like "citizens as sensors" or "volunteered geographic information" (VGI), i.e. volunteered sharing of location-based information with others through the internet, could be valuable (Goodchild, 2007; Sui et al., 2013). VGI approaches have already been a compilation for navigation map databases: the most prominent is OpenStreetMap (OSM), where everyone can edit the map, or GoogleMaps, where pictures or evaluations from users enrich the map (Dobson, 2013). For routing and mobility app developments, the option to voluntarily add local knowledge about pleasurable route aspects could be integrated. However, as discussed by Dobson (2013), technical difficulties of integrating too much information in a map have to be considered, as should a possible information overload (discussed in Article I, and stated by the participants in Article IV). VGI can be valuable for decision-makers, because it enables residents to integrate their local knowledge into planning processes: residents are "supposedly closer to the phenomena, can identify changes, and report those changes more quickly than government employees reliant on infrequently collected data" (Johnson & Sieber, 2013, p. 66). The fact that mobility apps lack participatory approaches (Article I) shows that there is potential to further integrate and try out participatory tools in mobility apps.

However, as also demanded by the participants in this thesis (Article IV), it is important not to see "citizens as sensors" (Goodchild, 2007), but "citizens as partners", meaning actively involving them in the research and planning process (Johnson & Sieber, 2013). It is a matter of strengthening an active civil society (Johnson & Sieber, 2013), which engages and has a saying in planning healthy and pleasant urban space. In most citizen science approaches, for example participatory pollution sensing (see Helbig et al., 2021), people record their environment without being an active collaborator in the research process (Haklay, 2013). As this thesis has shown, the participants were eager to be involved (Article IV), and showed a high interest in exchanging local knowledge with one another and the researcher (Article III and IV). It is valuable to involve users, include their needs and consider the urban context when developing information and communication technologies which aim at making urban mobility more sustainable and efficient (Lenz, 2015). With participatory methods, such as co-creation workshops, different stakeholders including civil society can be involved in research and planning processes which can improve the acceptance of new developments (e.g. planning measures, new concepts) (Gebhardt, 2021). The participants of this thesis have given new perspectives on healthy and pleasant commuting and on possible information and communication options (Article II-IV). Being in close collaboration with potential users is decisive for designing ICTs adapted to users' needs.

As already presented, the findings of this thesis led to the idea of creating a pleasant routing app and emphasized the importance of other exposure communication strategies. However, the refusal of receiving information due to a lack of options was as well a central issue for the participants (Article IV). Exposure information should not only be presented and passively received by the users, who need to find solutions themselves, but should improve their threat and coping appraisal (see section 2.3 or Article IV). Therefore, it is a matter of not only presenting objectively measured data, but to make this data subjectively interpretable and understandable, so that people are able to act accordingly. Following the results of this thesis regarding pollution communication, new digital developments such as augmented reality (AR) or virtual reality (VR) could be valuable to communicate exposure to laypersons in a more vivid way. For example, estimated particulate matter based on city-wide or wearable sensor networks could be visualized as small or bigger dots floating in the air using AR while walking or cycling. Using VR and headphones, a virtual city with visualized pollution estimates or noise can give an understanding of pollution patterns. Hence, pollution could become relatable: particulate matter close to motorized traffic can be visualized or the lowering of pollutants with increasing distance to the emitter can be demonstrated, for example in schools or driving schools. In the last few years studies have developed technologies like these: for example AR smartphones apps visualizing air pollution in cities (see Mathews et al., 2021), applying AR for educating school children about their exposure (see Campana et al., 2020) or taking VR to visualize urban noise standards city-wide and in specific locations (see Berger et al., 2019). Next to these new technologies, more simplistic approaches for informing people on a city-wide level could be the implementation of drawings, lines or digital warnings on the sidewalk, which could indicate that the increasing distance to the street lowers exposure. Moreover, particulate matter sensor networks using low-cost sensors visualizing measurements via maps or as part of a weather forecast could show air pollution to people who have not much engaged with the topic yet (Hamm, 2020). Making pollution numbers relatable is demanded by the participants (Article IV), hence, approaches like these could be useful.

Finally, mobility apps and other communication strategies may only be a supplement to good urban design, urban governance and transport planning (see conclusion in Article I). This is also stressed by Lyons (2018), who demands that "technology is only one means to the end goal of smart urban mobility with good urban design something not to be undervalued" (Lyons, 2018, p.13). Referring back to the initial questions of this thesis, it becomes evident that providing personalized[32] exposure information for inevitable daily routes is not useful if there are no other, healthier or more pleasant route options. Therefore, the following section provides implications for research and planning how to implement pleasant and healthy routes.

5.3 Contribution to scientific research and implications for policy and planning

This thesis contributes to scientific research in the field of geography, mobility research and exposure research and gives suggestions for healthy and pleasant mobility planning. Firstly, the contribution to and implications for scientific research will be discussed. Following this, implications for policy and planning will be presented.

Contribution to and implications for scientific research

The contribution of this thesis to scientific research is twofold. Firstly, this thesis enriches the research fields of health risk communication and exposure research by considering it from a mobility research perspective. Secondly, it brings together perspectives coming from the mobilities paradigm, practice theory and cognitive geography and connects it to exposure research (cf. section 2).

Primarily, this thesis contributes to research following the "new mobilities paradigm" (Sheller & Urry, 2006), by specifically investigating the movement of cyclists and pedestrians, their embodied experiences, perceptions, practices and perceived health on-the-move. In the field of human geography, the mobility and environmental perception of people has traditionally been researched, for example their movement in time and space (see Hägerstrand, 1970) or their perception of the urban environment (see Lynch, 1960). In recent years, the practices during

[32] Personalized information means air pollution or noise exposure information for the respective route or trip of a person, and not general information on health impacts of air pollution or noise. It thus refers to the definition of Becker al. (2021) for "personalized sensor feedback". It is about en route exposure information (e.g. via a city-wide map, an app or signs in the city based on city-wide or portable sensors).

movement and practiced mobility, following practice theory, have gained attention in human geography as well (Schäfer & Everts, 2019). Drawing on these research fields was successful for this thesis to dive deep into commuters' perceptions and practices on-the-move and valuable for linking them with their exposure to air pollution and noise pollution en route. Recently, exposure and health research have also given the movement of people and their dynamic exposure patterns attention, specifically due to the development of portable, low-cost sensors making it possible to record locally changing personal exposure over time and space (Helbig et al., 2021; Larkin & Hystad, 2017; Snyder et al., 2013). Exposure research has traditionally been characterized by stationarity and relied on models which do not take spatially varying variables into account, hence, may lead to an underestimation of environmental-health impacts (Kwan, 2021; Larkin & Hystad, 2017). By investigating perceived and measured air pollution and noise on-the-move, this thesis' exposure assessment acknowledges the importance of locally changing exposure, both perceived and measured.

This thesis contributes to these new and traditional research fields and creates a joint perspective on movement and (perceived) health and wellbeing on-the-move by following a mobile ethnographic approach. As presented, all addressed research fields have recently demanded to take the movement of people and spatial changes of environmental situations into account. Hence, the movement itself was central in this thesis. To research movement, moving with the research subject can provide deep insights into their experienced mobility. Also, health research is argued to lack mobile, i.e. non-stationary methods, which can be addressed through mobile interviewing such as go- or ride-alongs (King & Woodroffe, 2017). This thesis is embedded in the aforementioned research fields, which all acknowledge the importance of movement and of studying people on-the-move. Hence, the addressed research fields were all connected in this thesis through the consideration of movement, which came to the fore of investigation. This provided a joint understanding of mobility and exposure.

Furthermore, integrating health-behaviour theories (cf. section 2.3 and 2.4) with the other theoretical perspectives (cf. section 2.1 and 2.2) was valuable for understanding mobility-related health communication needs. Giving health topics attention in mobility research and applying health concepts and theories can enrich research on mobility and health. By drawing on health research theories during the focus groups and the go- and ride-alongs, the perceived health of cyclists and pedestrians as well as their protective practices became a research focus (see Article II, III and IV). Applying health-theories when researching mobility was valuable to explore health protective practices en route. Specifically, the PMT and EHL highlighted the importance of self-efficacy and response efficacy (PMT) as well as the importance of participatory and community engagement (EHL). These components should be considered when researching and designing exposure information to prevent information denial (see Article I and IV or Becker et al. (2021)).

Implication for urban and transport planning and policy

The results of this thesis have shown that cyclists and pedestrians often tried to avoid polluted areas with high volume of motorized traffic. However, by doing so, they often had to face other obstacles, for example less safety en route, less attractive routes or longer, less direct and less comfortable routes (see Article III and IV). On the one hand, this shows how important it is to ensure routes with low motorized traffic volume and low pollution, which are also fast, safe and convenient. This has already been acknowledged by the cycling planning of Berlin[33] (SenUVK, 2021). On the other hand, the results of this thesis highlight the importance of interesting, appealing and health-promoting route environments. By accompanying cyclists and pedestrians on-the-move, factors relevant for urban transport planning could be discovered. These will be presented in the following. Promoting these factors can increase cyclists' and pedestrians' perceived health, wellbeing and satisfaction of the transport system, but also has the potential to balance high air pollution or noise exposure en route (see Article III and IV).

Next to the foremost essential demand to lower pollution in the city (SenUVK, 2019a, 2019b), this thesis proposes to give more attention to the following planning implications. The following recommendations are grounded in the statements the participates have made en route (go-/ride-alongs) or in retrospect (focus groups), the practices observed by the interviewer while accompanying them and result from observing their route environment and how they engage with it (go- and ride-along). In the following planning and policy recommendations, the "**<u>why</u>**" is based on the findings of this thesis (Article II, III and IV) and at some instances supplemented by existing literature. The "**<u>how</u>**" formulates suggestions for planning measures, which derive from these findings. The implications for policy and planning as derived from the findings of this thesis are as follows:

- **Preserve and implement greenery and even small pieces of plants or grass verges along/close to cycling and walking routes**

  <u>Why</u>: Seeing and smelling greenery calms down, increases perceived health and wellbeing and can balance upcoming stressful or polluted routes

  <u>How</u>: Plant trees, flowers, grass verges along the routes, make space for urban gardens, routing through greenery/parks

- **Protect and create habitats for animals along cycling and walking routes**

  <u>Why</u>: Seeing animals makes the trip interesting, cyclists and pedestrians feel attached to nature and state to forget that they are in a big city

[33] Germany is still dominated by individual motorized transport (Nobis et al., 2018). In Berlin individual motorized transport are commonly used, as is public transport, and walking and specifically cycling are gaining attention (Gerike et al., 2018; SenUVK, n.d.; SenUVK, 2021). Berlin is currently planning to improve its cycling infrastructure, having attractive and safe cycling lanes alongside and away from motorized traffic (so called "bicycle highways") with connections with city-wide importance (SenUVK, 2021).

How: Preserve and protect natural habitats in the city where animals, e.g. foxes, birds or rabbits, can live, create paths/cycling routes through greenery where animals may be observed

- **Preserve and implement water areas or water views along cycling and walking routes**

  Why: Seeing and smelling water improves wellbeing, small glimpses of water (e.g. on a bridge) can balance highly trafficked areas, seeing water perceivably cools down on hot days

  How: Bridges over rivers, routes alongside rivers, water ponds or lakes, fountains

- **Create vast views along/close to cycling and walking routes**

  Why: Prevents the feeling to be "trapped" in street canyons, seeing the sky in built-up areas improves wellbeing and calms down

  How: Provide open space where the sky is visible, design street corridors where one has a wide view, big open green spaces, avoid "street canyons"

- **Built cycling/walking infrastructure along interesting sites or highlights**

  Why: Increases curiosity, interest and joy while cycling/walking, prevents a boring trip and improves wellbeing, makes people feel attached to city (e.g. city landmarks)

  How: Plan routes passing landmarks, interesting sites or historical buildings, preserve and build aesthetic urban form, built aesthetic subway stations, allow urban dwellers to create and design the city (e.g. official places for graffiti, urban gardening)

- **Guide cycling/walking routes along open public and vibrant spaces where people take ownership of their city**

  Why: Feeling related to "own" city when cycling/walking through it, creates a feeling that "there is a place" for people living there, increases wellbeing and quality of life

  How: Routes passing e.g. playgrounds, allotment/urban gardens, parks where one can barbeque/picknick or do sports (e.g. fly a kite, skateboard, play table tennis)

- **Promote streets with local shops, cafés and bars and enhance walking and cycling infrastructure alongside local shops, cafés and bars**

  Why: People feel attached to "their" city when cycling/walking past little local shops/bars/restaurants, increases community feeling, improves trip experience due to an increase of interest and curiosity

  How: Preserve and promote local shops/bars/restaurants, improve cycling/walking infrastructure alongside (e.g. wide sidewalks so that chairs and pedestrians have space)

- **Increase distance to and lower exposure from motorized traffic**

  <u>Why</u>: Lowering of inhaled doses of air pollution and exposure to noise prevents physical and mental health impacts (Krzyzanowski et al., 2005; WHO, 2011)

  <u>How</u>: Built cycling/walking routes with a distance/away from to road traffic (attention to safety at intersections), increase distance to emitters at traffic lights, lower amount of motorized traffic close to cycling/walking routes, built pedestrian zones, improve air filters and noise abatement in public transport

- **Consider measurable noise and air pollution when planning for walking and cycling**

  <u>Why</u>: Prevents physical and mental health impacts (Krzyzanowski et al., 2005; WHO, 2011) of cyclists and pedestrians, increases the share of cyclists and pedestrians when healthier and safer routes are offered (SenUVK, 2021)

  <u>How</u>: Give pollution estimation higher importance when planning routes or installing traffic lights (e.g. waiting times and distance to cars), built air corridors for air exchange

The proposed planning implications do not only benefit cyclists and pedestrians, but have also co-benefits. For example, promoting urban ecosystem services such as greenery, water and less pollution benefits quality of life in cities, can prevent long-term economic and social costs and increase urban resiliency against, for example weather extremes such as heat waves, flooding or storms (Gómez-Baggethun & Barton, 2013; IPCC, 2022). This is of high importance concerning the high confidence in an increase in weather extremes in urban areas due to climate change (IPCC, 2022). Moreover, lowering pollution, improving access to greenery and improving physical activity conditions in cities can improve health for all residents and is estimated to lower mortality rates and may increase average life expectancy (if international recommendations are followed) (Mueller et al., 2017). The proposed transport planning suggestions can have positive impacts for all urban dwellers. Promoting vibrant places and liveable, aesthetic and interesting urban areas may not only be beneficial for the people living in the city, but also makes the city attractive for tourists or people wanting to move there, hence, might have economic benefits. Ultimately, planning for a liveable city may also increase residents overall satisfaction of policy and planning authorities and may therefore be desirable for urban policy and planning practitioners.

Furthermore, the findings of this thesis have stressed the importance of integrating commuters' knowledge and opinions into planning processes. To gather data on experiences and commuting practices, citizen-adapted urban planning could also apply mobile, on-the-move methods. Marquart and Schicketanz (2022)[34] discuss benefits and barriers of mobile, on-the-move methods for urban and transport planning, partly based on this thesis' go- and ride-along

[34] The link to the paper and its abstract is attached in Appendix A.

approach. Some examples of participatory mobile methods are community walks or community mappings, which can be done with a group organized by the municipality to collectively discuss (un)pleasant route environments on site (Marquart & Schicketanz, 2022). However, it is comparably time-consuming and financially demanding, as are many participatory planning tools (Nared, 2020). Digital participatory tools with geo-locating address these barriers. Using a digital map where cyclists or pedestrians can pinpoint and comment on positive or negative experiences en route, similar to the GPS-tracking approach of this thesis (section 3.3), can help to identify hotspots and might be of interest for planning (Snizek et al., 2013). Subjective evaluations of certain places or perceived pollution hotspots as revealed, for example in Article II and III, could be discovered. Some cities already apply those tools: for example, the senate of Berlin provided a digital map where urban dwellers could geo-locate areas where they experience traffic noise, which resulted in a noise action plan (SenUVK, 2019b). Another project in Prague, Czech Republic, let district residents and pupils map perceived unsafe routes and presented the maps to the police and district representatives (Pánek, 2019).

These participatory approaches could address the discussed lack in trustworthiness expressed by the participants in the focus groups (Article IV). The potential of participatory approaches has been underused in transport planning in Europe, but becomes increasingly relevant (Nared, 2020). Referring to the participants' demand that decision-makers should plan healthy routes (Article IV), strengthening participatory planning approaches could improve environmental justice. Partnerships between researchers, decision-makers and affected residents are decisive for understanding and improving environmental justice in cities (Lakes et al., 2013), hence, it should be ensured that all urban residents can have a saying in planning decisions. If both digital (e.g. smartphone-based) and analogue (e.g. community walks) participatory approaches are applied, not only "digital-natives" get a voice, but also residents unfamiliar with digital devices can be reached (Gebhardt et al., 2021). For improving environmental justice in cities, it could be valuable to take an environmental justice index into account, which integrates air and noise pollution, land use data and socioeconomic data, but also integrates subjective evaluations of residents gathered by participatory methods (as the index e.g. developed by Lakes et al. (2013), or Shrestha et al. (2016)). Therefore, perceived and measurable environmental (in)justice can be revealed.

For addressing the discovered lack of trustworthiness in political actions (see Article IV), decision-makers could consider the concept of Environmental Health Literacy (EHL) when implementing measures. Drawing on the steps of EHL could be fruitful to design public information campaigns which prevent the discovered information denial (Article IV). As discussed in the focus groups, schools could include air pollution or noise topics in their curriculum, for example in combination with education on mobility. Driving schools could give pollution effects more attention so that drivers are knowledgeable about health impacts (proposed by the participants in Article IV). Campaigns in the media, e.g. radio, social media or TV, which increase awareness of urban air pollution and noise in the community were also suggested by the participants (Article IV). Recognition and understanding could be raised by showing how much premature deaths can be related to air pollution in Europe (see EEA (2020a)) or which diseases are associated with noise, for example cardiovascular effects or cognitive development in children (EEA, 2020b). Importantly, this knowledge needs to be linked to self-efficacy: the presented pleasant routing app or general suggestions to protect oneself should provide information on how to effectively and feasibly protect oneself from air pollution or noise. Ultimately, it may lead to creation and community change (see EHL in section 2.4 and Article IV). However, as discussed in Article IV or by Becker et al. (2021), providing information without changing the external circumstances through measures for lowering pollution can backfire and result in resignation and denial. Information campaigns need to be backed up by policy and planning measures which improve health and wellbeing in cities.

5.4 Reflections on the study design and applied methods

The methodological approach of this thesis poses both challenges and opportunities. These should be considered and will now be presented. Moreover, the Covid-19 pandemic disrupted the data gathering. The impact of this disruption will also be discussed.

The study design and methods: opportunities and challenges

Firstly, the **mixed-method approach** of this thesis was both challenging and beneficial. It has integrated qualitative and quantitative approaches in more than one step of the research design: within the research questions, in the data gathering and analysing phase as well as for interpreting the results. The quantitative approach, i.e. the measurement data, beneficially complements the qualitative approach in the go- and ride-alongs and focus groups. Applying wearable sensors during go- and ride-alongs supported the interpretation of the qualitative data. It underpinned the qualitative data with the actual measured exposure. However, complementing qualitative interview data with quantitative measurement data can also be challenging, because they follow a different research logic and need to be translated for comparison: for example, the qualitative interview data need to be translated into something quantifiable, which can be put in relation to the measurements (e.g. by using value-oriented codes such as ‘good’, ‘neutral’ or ‘bad’) or the quantitative data translated to make it referable to the qualitative data (e.g. measurable high pollution, low pollution) (see Article II or Steinmetz-Wood et al. (2019)). In this thesis, which prioritizes the qualitative approach, the measurement data was translated into percentiles to make them relatable to the qualitative statements and some qualitative statements were translated to value-oriented codes to make them relatable to the measurements (pleasant, unpleasant). The measurements supported the interpretation of the qualitative data, which was highly valuable to explore on site exposure perceptions as well as wellbeing and perceived health en route.

The georeferenced quantitative and qualitative data both incorporate **the spatial level**. Transferring georeferenced qualitative and measurement data into a map made it possible to visualize, analyse and interpret both qualitative and quantitative data together in relation to the spatial situation. Qualitative data with spatial relations ("qualitative GIS" (Cope, 2009)) can be enriched by geo-localized measurements and other data, for example land use data (as discussed in Article II), which have proven successful in this thesis. The application of **mobile methods** combined with **focus groups** was also successful. This can be shown in three examples: (a) During the go- and ride-alongs, the interviewer is invited to join the interviewee's personal commuting route in his/her daily life, which creates a relationship. This relationship was important for the following focus groups, because the interviewees were already familiar with the interviewer and power imbalances could be reduced. (b) In the focus groups all interviewees had a common experience, because all had taken part in the go- or ride-alongs. This enhanced the focus group atmosphere and the interviewees exchanged experiences enthusiastically, seeming even happy to share their experiences with other participants, ensuring an open and interactive focus group atmosphere. (c) The different steps of the research design built on one another very well: the questions during the go-/ride-alongs made the interviewee aware of air pollution and noise, knowing that exposure is getting measured increased curiosity and the following GPS-tracking deepened their awareness and made them cautions about route alternatives. In the final focus groups, this served as a good background to discuss exposure communication and information. Each step alone may not have given such comprehensive and in-depths insights.

Nevertheless, an extensive mixed-methods study design with three steps of data gathering takes a lot of preparation and time. It also demands time and commitment from the participants. Hence, there may be a **sample bias**: the people who participated are probably interested in the topic, may be critical or curious about air pollution and noise, may be specifically interested in engaging in research and have time or resources for taking part. Therefore, this potential "special interest groups", which may represent only a minority of possible transport users, can dominate the discussion about transport and mobility measures leading to an "exclusive public input into transport policy" (Bickerstaff et al., 2002, p. 71; Nared, 2020). This challenge was partly met by distributing the call for participants among different channels, among them neighbourhood networks or social media, so that different groups of people could be reached. Moreover, letting the interviewee choose day and time for the go- or ride-along and having the focus groups in the late afternoon hours ensured that people with time constrains could participate. However, as also argued by Tomsho et al. (2019) and in Article III and IV, vulnerable people and hard-to-reach groups, such as, for example older people, people with health problems or children – who are most in need of exposure protection – might not have been reached with this study. They might also have been excluded because commuting routes were investigated. The aim of this thesis was clearly on people who commute to work (i.e. not children or pensioners). This social selectivity should be considered and future studies could specifically take these groups into account. It is important to ensure that participants who can easily articulate their opinions do not overshadow others, who are either not reached at all or who are not heard (Nared, 2020). Further integrating vulnerable groups is needed and their capabilities and abilities should be addressed when developing participation processes, both for exposure communication research (Tomsho et al., 2019) and transport research and planning (Gebhardt & König, 2021; Nared, 2020).

Based on the rather exploratory nature of this thesis, the **sample size** is comparably small and not representable. Therefore, the results do not give (and do not aim to give) any conclusions in statistical terms for a larger group of people. As common in qualitative research, the aim is to investigate the research subject or phenomenon under investigation and identify how it is constituted, rather than its statistical characteristic (Lamnek & Krell, 2016). Generally, qualitative approaches are missing in environmental risk perception research (Noel et al., 2021). The qualitative approach of this thesis explored exposure perceptions, en route experiences, commuting practices and exposure communication needs, which a quantitative approach could not have done in such depths. Hence, it was shown that qualitative approaches offer great possibilities to research people's perceived health and wellbeing related to their mobility practices and needs.

As for the discovered **practices and perceptions**, it should be noted that the interviewer's presence influences the "normally private stream of perceptions, emotions and interpretations the research is trying to capture" (Hein et al., 2008, p. 1276). The interviewees' answers and the observed practices on-the-move are a result of the interaction between the interviewer, the interviewee and the environment. On-the-move interviews lead to an "experience building" (Kowalewski & Bartłomiejski, 2020) between interviewee and interviewer. This results in a common reality, which may differ from the actual 'reality' of the interviewee's commute. The results have to be seen in light of this and cannot be regarded as the 'normal' practices and perceptions of the interviewee. The fact that the interviewer asked questions, engaged in the participants' environment and cycled or walked next the interviewee intruded their "private dimensions of lived experiences" and created a "contrived social situation" (Kusenbach, 2003, p. 464). This was shown, for example by the fact that interviewees started asking questions to the interviewer and sometimes reported that talking with someone while cycling was a new experience for them (see Article IV). They also reported that questions regarding air pollution and noise perception increased their awareness of these stressors en route. The go- and ride-along situation itself and the reported environmental perceptions were experienced as a rather artificial situation, at least partly. As discussed for qualitative research in general, the underlying values and views of the researcher when gathering and interpreting qualitative data, and the power relations between researcher and research subject may influence the data gathering and it is highly important to be aware of that when reflecting upon the gathered data (Cloke et al., 2004). Go- and ride-alongs make it possible to reveal aspects that "tend to be remain hidden to observers and participants alike" (Kusenbach, 2003, p. 478). Hence, also the interviewees may have experienced their environment in new and unforeseen ways (see for example how they perceived noise after being made aware of it, cf. Article IV). This is also regarded as an interesting and valuable result of the go- and ride-alongs and is further discussed in Article II.

Thirdly, the usage and selection of **wearable sensors** poses challenges. The applied wearable sensors measured particulate matter and dB(A). Other pollutants could be of interest as well, especially for studies which aim at giving the measured exposure a higher priority. Wearable sensors have increasingly been deployed in exposure research and many sensors exist (see Helbig et al., 2021). Sensors which dynamically detect multiple pollutants, including e.g. NO_2 or Ozone, or which measure frequencies of sounds to detect the source of the noise could be applied. However, the usage of low-cost wearable sensors also poses its difficulties. In the underground train the GPS-based smartphone noise sensor did not properly record and sometimes noise recording difficulties took place[35]. Moreover, wind or other sounds (e.g. the bicycle when riding on rough ground) may have influenced the noise recording. Recorded noise may not always represent traffic noise. However, it should be noted that also other noise sources (e.g. wind or cobble stones) can be perceived as an unpleasant sound en route. The voice recordings have been used to detect whether measurable loud areas were due to traffic noise or other noise sources. Generally, the noise measurements have been interpreted with caution (see Article II and Article III). Moreover, the usage of the MovingLab tracking app which tracked the participants independently on-the-move and automatically detects their mode posed some difficulties. Privacy issues were stated during the empirical phase: interviewees did not feel comfortable to share their tracked route in the focus groups on a digital touch screen in front of others. Privacy concerns are often discussed when applying individual health and tracking devices (Kamel Boulos & Yang, 2021). In the second and third focus group the digital touch-screen was not applied (due to the Covid-19 pandemic and restrictions in meeting indoors), hence, the tracking routes were only partly shared with the group. This was regarded as more appropriate; however, it hindered an in-depth discussion about the tracked route choices.

Finally, the **study area** of the thesis will be reflected to give hints of its transferability. The study took place in Berlin, Germany. Berlin is a city which is increasingly implementing cycling infrastructure due to the mobility act from 2018 (SenUVK, n.d.), whose inhabitants increasingly cycle (SenUVK, 2017) and whose mobility committee has newly developed a pedestrian strategy in 2020 (SenUVK, n.d.). Moreover, Berlin is a green city, with low topography and a continental climate, hence, walking and cycling is easily feasible (SenUVK, 2021). Moreover, Berlin has a well-developed and used public transport (Gerike et al., 2018). The experiences, perceptions and practices during commuting in this city have to be considered in light of the

[35] With three participants the noise measurements were interrupted. The missing measurement data has not been analysed and was not considered in the objectively measured and subjectively perceived data analysis.

rather beneficial circumstances. In low or emerging cycling cities, the experiences of the inhabitants regarding active commuting can be different. Aspects such as perceived safe bicycle infrastructure have a high priority there (Desjardins et al., 2021). The findings of this thesis can give insights into how cycling and walking is experienced, how to research practiced mobility and related exposure and how cyclists and pedestrians could be informed about healthy routes. Therefore, the methods and results of this thesis provide a starting point when planning research or measures regarding healthy cycling and walking in other cities.

Effect of the Covid-19 pandemic on the study

One important issue that influenced this thesis' data gathering is the Covid-19 pandemic[36]. The Covid-19 pandemic emerged in early 2020 during the data gathering phase. Hence, the first ten participants were recruited and took part before the Covid-19 outbreak, and the other eighteen participants after the outbreak and during the pandemic. The data gathering during the Covid-19 pandemic took place in a phase of the pandemic when restrictions were comparably low. Limitations and opportunities deriving from these circumstances will be elaborated in the following.

Firstly, the Covid-19 pandemic made the recruiting of participants difficult, because people could get infected and hence, a call for face-to-face interviews and focus group discussions may have been a deterrent. Additionally, many people worked at least partly from home during the pandemic (Kolarova et al., 2021) and commuting to work was not as common as before – and will maybe stay lower than before in the long-run (Currie et al., 2021). Since the study aimed at commuting routes, this was influencing the recruitment. Moreover, the usage of public transport has declined in Germany (Eisenmann et al., 2021) and the fear of infecting oneself in public transport has increased and may still exist in the in long-term (as shown in Melbourne, Australia (Currie et al., 2021)). This fear and the need to wear face masks in public transport may have resulted in less participants using and wanting to be interviewed in public transport. The smaller number of participants who used public transport after the Covid-19 outbreak may reflect that.

Secondly, the Covid-19 pandemic has reshaped the quality of life in the city extensively (Mouratidis, 2021). Studies suggest that green spaces or open public spaces, which provide space for social interaction or leisure activities, became more essential during the pandemic (Mouratidis, 2021). This may have led the sample interviewed during the pandemic to think differently about the external environment and daily routes compared to the pre-pandemic sample. It is possible that the stated importance of social cues, of leisure areas, of bars, restaurants or seeing other urban dwellers could, at least partly, be a result of the experiences made during the pandemic and related social restrictions. However, these factors were already

[36] For more information on the Covid-19 pandemic see the official website of the WHO: https://www.who.int/emergencies/diseases/novel-coronavirus-2019

stated as important by the interviewees who took part before the pandemic. These aspects may just have become more important during the pandemic.

Finally, during the Covid-19 pandemic the public has followed the "usually concealed process of building scientific understandings" (Caulfield et al., 2021, p. 405), because the public could follow scientific discussions regarding the Covid-19 pandemic in the media. The discussion about scientific findings took place publicly, including consensus and disagreement in the scientific community, which impacted public perceptions and acceptance of preventive strategies (Caulfield et al., 2021). For example, following the declaration of the pandemic, public awareness regarding its health risks increased and resulted in increasing searches for Covid-19 related health information as well as changes in mobility practices (Jun et al., 2021; Schoenherr & Thomson, 2020). In this thesis, the participants who took part after the Covid-19 outbreak may have been more aware and sensitive about health issues – specifically inhaling particles – and may have more knowledge on scientific health topics as a result of the media discussions following the Covid-19 outbreak. Moreover, they may be more motivated to undertake health protective actions, because they were used to protect their health more extensively during the pandemic. For example, one interviewee stated that wearing masks is common due to the Covid-19 pandemic, so he would do it for air pollution as well, whereas another interviewee before the Covid-19 outbreak stated he would never wear a mask because of air pollution. Face masks for protecting oneself against air pollution exposure could become more societally acceptable as a result of the Covid-19 pandemic (Ravindra et al., 2022).

Summarizing, the Covid-19 pandemic has clearly had an impact on the data gathering of this thesis, however, it may just have reinforced already existing needs, requirements and protective motivations of cyclists and pedestrians. As for the future, Covid-19 has shed light on the importance of healthy living, healthy urban planning and health promoting policies. The pandemic emphasized the importance of breathing non-polluted air[37], the need for having green spaces and open public space where people can meet and shed light on the benefits of cycling and walking as healthy modes of transport. Specifically, it drew attention to modes of transport which are not only promoting physical health, but which also pose less danger of infectious diseases (compared to closed-up public transport) (Mouratidis, 2021). In that sense, the outbreak of Covid-19 can be regarded as an opportunity to place human health topics in the center of attention.

5.5 Outlook and concluding remarks

This thesis has given insights into the commute of cyclists and pedestrians in Berlin, Germany, and has explored possibilities to inform these active mode users about a healthy and pleasant trip. Promoting sustainable mobility, i.e. by making cycling and walking a pleasant and healthy

[37] See discussions about findings that Covid-19 was specifically harmful for people living in areas where high air pollution levels were measured (Travaglio et al., 2021), however, more research is needed (EEA, 2020a).

mobility choice, could be a fruitful way forward to create green and healthy cities that "go far beyond simply reducing CO2 emission" (Nieuwenhuijsen, 2016, p.167). Approaches to improve sustainable mobility should also prioritize health, and specifically air pollution and noise. These are two of the leading environmental health impacts in cities (Hänninen et al., 2014). Additionally, it is crucial to consider as well the subjective health experiences and wellbeing of cyclists and pedestrians on-the-move, alongside actual measurable pollution.

For future research it is recommended to draw on these findings. The focus on health, reinforced due to the Covid-19 pandemic, should be deepened and health topics should receive more attention in the field of transport and mobility. Meanwhile, exposure and environmental-health research could draw on the perspectives of the disciplinary field of geography and mobility by expanding its view towards subjectively perceived and mobile exposure assessments.

Moreover, this thesis has emphasized the need to actively involve transport users in the research and planning process for creating healthy and pleasant mobility. Hence, acknowledge them as experts of their own mobility needs. The research fields of citizen sciences, participatory research and citizens-as-sensors or -partners already show its importance. Participatory planning and governance should be strengthened to give people a voice in planning decisions and adapt the implemented measures to their requirements. In addition, users should be more integrated in the development, design and realization of mobility apps for pleasant and healthy route suggestions. Solely relying on commercial map providers may not meet the actual requirements of the users.

The requirements of commuters may also differ according to the region. It would be interesting to investigate the perceived exposure to air pollution and noise, related practices and experiences of urban dwellers in cities which face high levels of pollution. Moreover, investigating how they want to be informed and exploring their requirements regarding pollution prevention could be studied. On the contrary, taking a closer look on perceived and measured exposure and practices of people in cities with comparably very low pollution, much greenery and water and high mode share of cyclists and pedestrians would be of interest. Additionally, future studies could enrich the proposed methodological approach by additionally measuring physiological reactions during commute, i.e. measuring heart-rate, stress level or other body-related reactions (e.g. see the study from Kabisch et al. (2021) on physiological impacts from green space visits). Lastly, it would be of high interest to develop the proposed pleasant routing app (section 5.2 and Article IV) or integrate components of it in existing mobility apps, considering the conceptual framework for mobility app development (Article I). Future studies could test an app like the one proposed and investigate in how far it improves commuting experiences, perceived health and wellbeing.

Whereas this thesis has focused on cyclists and pedestrians (incl. public transport users), future studies could also investigate the sensory awareness of car users and investigate which factors are of importance for their personal exposure, health and wellbeing en route. This could also motivate them to change to healthier modes, such as walking or cycling. Generally, car users in traffic can have higher exposure than cyclists and pedestrians[38] (de Hartog et al., 2010; de Nazelle et al., 2017; Ramos et al., 2016). Future research should also focus on health and mobility needs of children, older people or other vulnerable groups, since they have comparably higher air pollution and noise exposure and are often more susceptible regarding air pollution or noise impacts (EEA, 2020a). It would be specifically interesting to investigate their perceived health, wellbeing and pollution exposure on-the-move.

Not least since the Covid-19 pandemic the topic of health has gained societal attention. Also concepts such as healthy cities, green cities or livable cities have become increasingly important in urban policy and planning (Nieuwenhuijsen & Khreis, 2019). Making cities green, healthy and livable also involves adapting cities to climate change effects, which is known to have severe consequences for human physical and mental health, while at the same time it is important to mitigate climate change in cities (IPCC, 2022; Revi et al., 2014). Promoting cycling and walking, but also public transport, can address these needs. They can be a cornerstone for developing a sustainable, i.e. liveable, healthy, environmentally friendly and just city of the future. This thesis has shed light on these active mode users and drew attention to their perceptions, experiences, practices and personal exposure whilst cycling or walking in the city. By exploring perceptions and exposure on-the-move, this thesis has placed the movement itself in the focus. The results emphasize the need to take the perceived environment whilst being on-the-move seriously. They shed light on the importance of considering traffic-influenced microenvironments and related dynamic personal exposure while moving and stress the need to acknowledge the perceived exposure and perceived health and wellbeing whilst on-the-move. Summarizing, the results of this thesis highlight relevant aspects of pleasant and healthy commuting which should be considered in research and planning, and also serve as a guide for future communication campaigns or information provision. It is essential to not only inform cyclists and pedestrians about pleasant and healthy routes, but also engage them in planning and information campaigns, acknowledging their mobility practices and perceptions en route. This can encourage more people to cycle or walk and ensure that cycling and walking in cities is a healthy *and* pleasant experience.

[38] As noted by, for example Ramos et al. (2016), the exposure of car users can be higher, however, the ventilation rate and inhaled doses of particulate matter can be higher for cyclists. Moreover, the exposure can differ depending on the pollutants, for example the measured exposure to particulate matter, ultrafine particulate matter, black carbon or carbon monoxide differs by transport modes (see de Nazelle et al., 2017).

References

Andersson, A., Winslott Hiselius, L., & Adell, E. (2018). Promoting sustainable travel behaviour through the use of smartphone applications: A review and development of a conceptual model. *Travel Behaviour and Society, 11*, 52-61.

Andringa, T. C., Weber, M., Payne, S. R., Krijnders, J. D., Dixon, M. N., Linden, R. V. D., de Kock, E. G. L. & Lanser, J. J. L. (2013). Positioning soundscape research and management. *Journal of the Acoustical Society of America, 134*(4), 2739-2747.

Apparicio, P., Carrier, M., Gelb, J., Séguin, A.-M., & Kingham, S. (2016). Cyclists' exposure to air pollution and road traffic noise in central city neighbourhoods of Montreal. *Journal of Transport Geography, 57*, 63-69.

Banister, D. (2008). The sustainable mobility paradigm. *Transport Policy, 15*(2), 73-80.

Barbieri, D. M., Lou, B., Passavanti, M., Hui, C., Hoff, I., Lessa, D. A., . . . Rashidi, T. H. (2021). Impact of COVID-19 pandemic on mobility in ten countries and associated perceived risk for all transport modes. *PLoS One, 16*(2).

Baxter, J. (2018). Qualitative Health Geography Reaches the Mainstream. In V. Crooks, G. Andrews, & J. Pearce (Eds.), *Routledge Handbook of Health Geography* (pp. 302 - 310). Abingdon and New York: Routledge.

Becker, A. M., Marquart, H., Masson, T., Helbig, C., & Schlink, U. (2021). Impacts of Personalized Sensor Feedback Regarding Exposure to Environmental Stressors. *Current Pollution Reports, 7*(4), 579-593.

Berger, M., & Bill, R. (2019). Combining VR visualization and sonification for immersive exploration of urban noise standards. *Multimodal Technologies and Interaction, 3*(2).

Bickerstaff, K. (2004). Risk perception research: socio-cultural perspectives on the public experience of air pollution. *Environment International, 30*(6), 827-840.

Bickerstaff, K., Tolley, R., & Walker, G. (2002). Transport planning and participation: the rhetoric and realities of public involvement. *Journal of Transport Geography, 10*(1), 61-73.

Bloom, B. S. (1956). *Taxonomy of Educational Objectives: the Classification of Educational Goal* (Vol. 1). New York: Longmans, Green.

Brody, J. G., Dunagan, S. C., Morello-Frosch, R., Brown, P., Patton, S., & Rudel, R. A. (2014). Reporting individual results for biomonitoring and environmental exposures: lessons learned from environmental communication case studies. *Environmental Health, 13*, 40.

Bubeck, P., Wouter Botzen, W. J., Laudan, J., Aerts, J., & Thieken, A. H. (2018). Insights into Flood-Coping Appraisals of Protection Motivation Theory: Empirical Evidence from Germany and France. *Risk Analysis, 38*(6), 1239-1257.

Büscher, M., & Urry, J. (2009). Mobile Methods and the Empirical. *European Journal of Social Theory, 12*(1), 99-116.

Campana, F. E., & Xavier Dominguez, F. (2020). Proposal of a Particulate Matter Measurement Device and an Augmented Reality Visualization App as an Educational Tool. *Proceedings of the 12th International Conference on Education Technology and Computers (ICETC'20*), 23-26. Association for Computing Machinery, New York, NY, USA.

Carpiano, R. M. (2009). Come take a walk with me: The "Go-Along" interview as a novel method for studying the implications of place for health and well-being. *Health & Place, 15*(1), 263-272.

Caulfield, T., Bubela, T., Kimmelman, J., & Ravitsky, V. (2021). Let's do better: public representations of COVID-19 science. *Facets, 6*(1), 403-423.

Chaney, R. A., Sloan, C. D., Cooper, V. C., Robinson, D. R., Hendrickson, N. R., McCord, T. A., & Johnston, J. D. (2017). Personal exposure to fine particulate air pollution while commuting: An examination of six transport modes on an urban arterial roadway. *PLoS One, 12*(11).

Cloke, P. J., Cook, I., et al., Crang, P., Goodwin, M. A., Painter, J., & Philo, C. P. (2004). *Practising Human Geography*. London: London: SAGE Publications.

Cole-Hunter, T., Morawska, L., Stewart, I., Jayaratne, R., & Solomon, C. (2012). Inhaled particle counts on bicycle commute routes of low and high proximity to motorised traffic. *Atmospheric Environment, 61*, 197-203.

Cope, M. (2009). *Qualitative GIS : a mixed methods approach / ed. by Meghan Cope and Sarah Elwood*. Los Angeles, CA: Sage Publ.

Cori, L., Donzelli, G., Gorini, F., Bianchi, F., & Curzio, O. (2020). Risk Perception of Air Pollution: A Systematic Review Focused on Particulate Matter Exposure. *International Journal of Environmental Research and Public Health, 17*(17).

Cresswell, T. (2010). Towards a Politics of Mobility. *Environment and Planning D: Society and Space, 28*(1), 17-31.

Currie, G., Jain, T., & Aston, L. (2021). Evidence of a post-COVID change in travel behaviour – Self-reported expectations of commuting in Melbourne. *Transportation Research Part A: Policy and Practice, 153*, 218-234.

Dal Fiore, F., Mokhtarian, P. L., Salomon, I., & Singer, M. E. (2014). "Nomads at last"? A set of perspectives on how mobile technology may affect travel. *Journal of Transport Geography, 41*, 97-106.

de Hartog, J., Boogaard, H., Nijland, H., & Hoek, G. (2010). Do the health benefits of cycling outweigh the risks? *Environmental Health Perspectives, 118*(8), 1109-1116.

de Nazelle, A., Bode, O., & Orjuela, J. P. (2017). Comparison of air pollution exposures in active vs. passive travel modes in European cities: A quantitative review. *Environment International, 99*, 151-160.

Degen, M. M., & Rose, G. (2012). The Sensory Experiencing of Urban Design: The Role of Walking and Perceptual Memory. *Urban Studies, 49*(15), 3271-3287.

DeLyser, D., Herbert, S., Aitken, S., Crang, M., & McDowell, L. (2010). *The SAGE handbook of qualitative geography* (1. publ. ed.). Los Angeles [u.a.]: SAGE.

Desjardins, E., Apatu, E., Razavi, S. D., Higgins, C. D., Scott, D. M., & Páez, A. (2021). "Going through a little bit of growing pains": A qualitative study of the factors that influence the route choice of regular bicyclists in a developing cycling city. *Transportation Research Part F: Traffic Psychology and Behaviour, 81*, 431-444.

Dobson, M. W. (2013). VGI as a Compilation Tool for Navigation Map Databases. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice* (pp. 307-327). Dordrecht: Springer Netherlands.

Downs, R. M., & Stea, D. (Eds.). (1973). *Image & environment: Cognitive mapping and spatial behavior* (1. publ. ed.). New York: Routledge.

EEA (European Environmental Agency) (2016a). *Transitions towards a more sustainable mobility system. TERM 2016: Transport indicators tracking progress towards environmental targets in Europe* (EEA Report No 34/2016). Luxembourg: Publications Office of the European Union.

EEA (European Environmental Agency) (2016b). *Urban adaptation to climate change in Europe 2016. Transforming cities in a changing climate* (EEA Report No 12/2016). Luxembourg: Publications Office of the European Union.

EEA (European Environmental Agency) (2020a). *Air quality in Europe – 2020 report* (EEA Report No 9/2020). Luxembourg: Publications Office of the European Union.

EEA (European Environmental Agency) (2020b). *Environmental noise in Europe — 2020* (EEA Report, 22/2019). Luxembourg: Publications Office of the European Union.

Eisenmann, C., Nobis, C., Kolarova, V., Lenz, B., & Winkler, C. (2021). Transport mode use during the COVID-19 lockdown period in Germany: The car became more important, public transport lost ground. *Transport Policy, 103*, 60-67.

Elias, W., & Shiftan, Y. (2012). The influence of individual's risk perception and attitudes on travel behavior. *Transportation Research Part A: Policy and Practice, 46*(8), 1241-1251.

European Commission (2021). *The New EU Urban Mobility Framework*. COM(2021) 811 final. Communication from the Comission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://transport.ec.europa.eu/system/files/2021-12/com_2021_811_the-new-eu-urban-mobility.pdf

Evans, J., & Jones, P. (2011). The walking interview: Methodology, mobility and place. *Applied Geography, 31*(2), 849-858.

Everts, J., Lahr-Kurten, M., & Watson, M. (2011). Practice matters! Geographical inquiry and theories of practice. *Erdkunde, 65*(4), 323-334.

Federal Ministry for Digital and Transport. (2022). *Fahrradland Deutschland 2030 - Nationaler Radverkehrsplan 3.0*. Berlin, Germany: Federal Ministry for Digital and Transport.

Fields, J. M. (1993). Effect of personal and situational variables on noise annoyance in residential areas. *The Journal of the Acoustical Society of America, 93,* 2753-2763.

Finn, S., & O'Fallon, L. (2017). The Emergence of Environmental Health Literacy-From Its Roots to Its Future Potential. *Environmental Health Perspectives, 125*(4), 495-501.

Flade, A. (2013). *Der rastlose Mensch - Konzepte und Erkenntnisse der Mobilitätspsychologie*. Wiesbaden: Springer VS.

Gatersleben, B., & Uzzell, D. (2000). The risk perception of transport -generated air pollution. *IATSS Research, 24*(1), 30-38.

Gebhardt, L. (2021). Understanding different car users as starting point for future mobility concepts – A co-creation approach. *Transportation Research Interdisciplinary Perspectives, 12*, 100485.

Gebhardt, L., & König, A. (2021). Wie begegnen wir dem Matthäuseffekt in Reallaboren? Selektivität in partizipativen Prozessen. *Raumforschung und Raumordnung | Spatial Research and Planning, 79*(4), 336-350.

Gerike, R., Hubrich, S., Ließke, F., Wittig, S., & Wittwer, R. (2018). *SrV - Mobilität in Städten 2018. Mobilitätssteckbrief für Berlin*. Technische Universität Dresden. https://www.berlin.de/sen/uvk/_assets/verkehr/verkehrsdaten/zahlen-und-fakten/mobilitaet-in-staedten-srv-2018/berlin_steckbrief_berlin_gesamt.pdf

German Environment Agency (2020). *Transforming the transport sector for EVERYONE - How to achieve more socially just and environmentally friendly mobility*. Dessau-Roßlau: German Environment Agency.

Gober, P. (2018). Environmental risks and hazards from a cognitive behavioral perspective. In D. R. Montello (Ed.), *Handbook of behavioral and cognitive geography* (pp. 322-334). Cheltenham, UK; Northampton, MA, USA: Edward Elgar Publishing.

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics, 86*, 235-245. doi:10.1016/j.ecolecon.2012.08.019

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal, 69*(4), 211-221.

Gössling, S. (2017). ICT and transport behavior: A conceptual review. *International Journal of Sustainable Transportation, 12*(3), 153-164.

Gray, K. M. (2018). From Content Knowledge to Community Change: A Review of Representations of Environmental Health Literacy. *International Journal of Environmental Research and Public Health, 15*(3).

Greene, M., & Rau, H. (2016). Moving across the life course: A biographic approach to researching dynamics of everyday mobility practices. *Journal of Consumer Culture, 18*(1), 60-82.

Guski, R. (1999). Personal and social variables as co-determinants of noise annoyance. *Noise Health, 1*(3), 45-56.

Hägerstrand, T. (1970). What about people in Regional Science? *Papers of the Regional Science Association, 24*(1), 6-21.

Haklay, M. (2013). Citizen Science and Volunteered Geographic Information: Overview and Typology of Participation. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice* (pp. 105-122). Dordrecht: Springer Netherlands.

Hamm, A. (2020). *Particles Matter: A Case Study on How Civic IoT Can Contribute to Sustainable Communities*. Paper presented at the Proceedings of the 7th International Conference on ICT for Sustainability, Bristol, United Kingdom.

Hänninen, O., Knol Anne, B., Jantunen, M., Lim, T.-A., Conrad, A., Rappolder, M., . . . Mekel Odile, C. L. (2014). Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries. *Environmental Health Perspectives, 122*(5), 439-446.

Hargreaves, T. (2011). Practice-ing behaviour change: Applying social practice theory to pro-environmental behaviour change. *Journal of Consumer Culture, 11*(1), 79-99.

Hein, J. R., Evans, J., & Jones, P. (2008). Mobile Methodologies: Theory, Technology and Practice. *Geography Compass, 2*(5), 1266-1285.

Helbig, C., Ueberham, M., Becker, A. M., Marquart, H., & Schlink, U. (2021). Wearable Sensors for Human Environmental Exposure in Urban Settings. *Current Pollution Reports*.

Hennink, M. M. (2014). *Focus group discussions*. New York: Oxford University Press.

Hillnhütter, H. (2016). *Pedestrian Access to Public Transport.* (PhD thesis UiS, no. 314). University of Stavanger, Stavanger, Norway. Retrieved from https://uis.brage.unit.no/uis-xmlui/bitstream/handle/11250/2422928/Helge_Hillnhutter.pdf?sequence=1&isAllowed=y

Hoover, A. G. (2019). Defining Environmental Health Literacy. In S. Finn & L. O'Fallon (Eds.), *Environmental Health Literacy* (pp. 3-18). Cham: Springer.

Hunecke, M. (2015). *Mobilitätsverhalten verstehen und verändern. Psychologische Beiträge zur interdisziplinären Mobilitätsforschung*. Wiesbaden: Springer VS.

IPCC (Intergovernmental Panel on Climate Change) (2022). Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.). *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

Johnson, P. A., & Sieber, R. E. (2013). Situating the Adoption of VGI by Government. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice* (pp. 65-81). Dordrecht: Springer Netherlands.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed Methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher, 33*(7), 14-26.

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research, 1*(2), 112-133.

Johnston, J. E., Juarez, Z., Navarro, S., Hernandez, A., & Gutschow, W. (2019). Youth Engaged Participatory Air Monitoring: A 'Day in the Life' in Urban Environmental Justice Communities. *International Journal of Environmental Research and Public Health, 17*(1).

Jun, S. P., Yoo, H. S., & Lee, J. S. (2021). The impact of the pandemic declaration on public awareness and behavior: Focusing on COVID-19 google searches. *Technological Forecasting and Social Change , 166*, 120592.

Kabisch, N., Püffel, C., Masztalerz, O., Hemmerling, J., & Kraemer, R. (2021). Physiological and psychological effects of visits to different urban green and street environments in older people: A field experiment in a dense inner-city area. *Landscape and Urban Planning, 207*.

Kamel Boulos, M. N., & Yang, S. P. (2021). Mobile physical activity planning and tracking: a brief overview of current options and desiderata for future solutions. *Mhealth, 7*, 13.

Kelly, C. E., Tight, M. R., Hodgson, F. C., & Page, M. W. (2011). A comparison of three methods for assessing the walkability of the pedestrian environment. *Journal of Transport Geography, 19*(6), 1500-1508.

Keuken, M., Sanderson, E., van Aalst, R., Borken, J., & Schneider, J. (2005). Contribution of traffic to levels of ambient air pollution in Europe. In M. Krzyzanowski, B. Kuna-Dibbert, & J. Schneider (Eds.), *Health effects of transport-related air pollution*. World Health Organization (WHO). https://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf

Khreis, H., van Nunen, E., Mueller, N., Zandieh, R., & Nieuwenhuijsen, M. J. (2017). Commentary: How to Create Healthy Environments in Cities. *Epidemiology, 28*(1).

King, A. C., & Woodroffe, J. (2017). Walking Interviews. In P. Liamputtong (Ed.), *Handbook of Research Methods in Health Social Sciences* (pp. 1-22). Singapore: Springer Singapore.

Kolarova, V., Eisenmann, C., Nobis, C., Winkler, C., & Lenz, B. (2021). Analysing the impact of the COVID-19 outbreak on everyday travel behaviour in Germany and potential implications for future travel patterns. *European Transport Research Review, 13*(1).

Kou, L., Kwan, M.-P., & Chai, Y. (2020). The effects of activity-related contexts on individual sound exposures: A time–geographic approach to soundscape studies. *Environment and Planning B: Urban Analytics and City Science, 48*(7), 2073-2092.

Kowalewski, M., & Bartłomiejski, R. (2020). Is it research or just walking? Framing walking research methods as “non-scientific”. *Geoforum, 114*, 59-65.

Krzyzanowski, M., Kuna-Dibbert, B., & Schneider, J. (2005). *Health effects of transport-related air pollutio*n. World Health Organization (WHO). https://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf

Kuckartz, U. (2014). *Mixed Methods Methodologie, Forschungsdesigns und Analyseverfahren*. Wiesbaden: Springer VS.

Kuckartz, U. (2020). *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung* (5. ed.). Weinheim: Beltz Verlagsgruppe.

Kuckartz, U., & Rädiker, S. (2019). *Analyzing Qualitative Data with MAXQDA*. Cham: Springer.

Kühl, J. (2016). Walking Interviews als Methode zur Erhebung alltäglicher Raumproduktionen. *Europa Regional, 23.2015*(2), 35-48.

Kühn, T., & Koschel, K.-V. (2011). Rolle und Ausgestaltung des Leitfadens und Stimulus Materials. In T. Kühn & K.-V. Koschel (Eds.), *Gruppendiskussionen: Ein Praxis-Handbuch* (pp. 97-137). Wiesbaden: VS Verlag für Sozialwissenschaften.

Kusenbach, M. (2003). Street Phenomenology: The Go-Along as Ethnographic Research Tool. *Ethnography, 4*(3), 455-485.

Kwan, M.-P., & Ding, G. (2008). Geo-Narrative: Extending Geographic Information Systems for Narrative Analysis in Qualitative and Mixed-Method Research. *The Professional Geographer, 60*(4), 443-465. doi

Kwan, M. P. (2021). The stationarity bias in research on the environmental determinants of health. *Health & Place, 70*, 102609.

Lakes, T., Brückner, M., & Krämer, A. (2013). Development of an environmental justice index to determine socio-economic disparities of noise pollution and green space in residential areas in Berlin. *Journal of Environmental Planning and Management, 57*(4), 538-556.

Lamnek, S., & Krell, C. (2016). *Qualitative Sozialforschung* (6. ed.). Weinheim, Basel: Beltz Verlag.

Larkin, A., & Hystad, P. (2017). Towards Personal Exposures: How Technology Is Changing Air Pollution and Health Research. *Current Environmental Health Reports, 4*(4), 463-471.

Lenz, B. (2011). Verkehrsrelevante Wechselwirkungen zwischen Mobilitätsverhalten und Nutzung von IuK-Technologien. *Informationen zur Raumentwicklung, 10*, 609-618.

Lenz, B. (2015). Vernetzung – Revolution für die urbane Mobilität der Zukunft? *e & i Elektrotechnik und Informationstechnik, 132*(7), 380-383.

Lindell, M. K., & Perry, R. W. (2004). *Communicating Environmental Risk in Multiethnic Communities*. Thousand Oaks: SAGE Publications.

Lindell, M. K., & Perry, R. W. (2012). The protective action decision model: theoretical modifications and additional evidence. *Risk Analysis, 32*(4), 616-632.

Liu, Y., Ouyang, Z., & Cheng, P. (2019). Predicting consumers' adoption of electric vehicles during the city smog crisis: An application of the protective action decision model. *Journal of Environmental Psychology, 64*, 30-38.

Lloyd, R. (1997). Geography and Cognitive Science. In R. Lloyd (Ed.), *Spatial Cognition: Geographic Environments* (pp. 1-24). Dordrecht: Springer Netherlands.

Lynch, K. (1960). *The image of the city*. Cambridge, Mass.: MIT Press.

Lyons, G. (2018). Getting smart about urban mobility – Aligning the paradigms of smart and sustainable. *Transportation Research Part A: Policy and Practice, 115*, 4-14.

Mack, B., & Tampe-Mai, K. (2012). Konzeption, Diskussionsleitfaden und Stimuli einer Fokusgruppe am Beispiel eines BMU-Projekts zur Entwicklung von Smart Meter Interfaces und begleitenden einführenden Maßnahmen zur optimalen Förderung des Stromsparens im Haushalt. In M. Schulz, B. Mack, & O. Renn (Eds.), *Fokusgruppen in der empirischen Sozialwissenschaft: Von der Konzeption bis zur Auswertung* (pp. 66-87). Wiesbaden: VS Verlag für Sozialwissenschaften.

Maddux, J. E., & Rogers, R. W. (1983). Protection motivation and self-efficacy: A revised theory of fear appeals and attitude change. *Journal of Experimental Social Psychology, 19*(5), 469-479.

Manderscheid, K. (2019). The Logic of Couplings: A Quantitative Practice-Theoretical Perspective on Mobilities. *Swiss Journal of Sociology, 45*(2), 161-183.

Marquart, H., & Schicketanz, J. (2022). Experiences of safe and healthy walking and cycling in urban areas: The benefits of mobile methods for citizen-adapted urban planning. *Transportation Research Procedia, 60*, 290-297.

Marquart, H., & Schuppan, J. (2022). Promoting Sustainable Mobility: To What Extent Is "Health" Considered by Mobility App Studies? A Review and a Conceptual Framework. *Sustainability*, *14*(1), 47.

Marquart, H., Stark, K., & Jarass, J. (2022). How are air pollution and noise perceived en route? Investigating cyclists' and pedestrians' personal exposure, wellbeing and practices during commute. *Journal of Transport & Health, 24*, 101325.

Marquart, H., Ueberham, M., & Schlink, U. (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.

Marquart, H. (under review). Informing about the invisible – Communicating en route air pollution and noise exposure to cyclists and pedestrians using focus groups. *Submitted to European Transport Research Review*.

Mars, L., Arroyo, R., & Ruiz, T. (2016). Qualitative Research in Travel Behavior Studies. *Transportation Research Procedia, 18*, 434-445.

Mathews, N. S., Chimalakonda, S., & Jain, S. J. I. V. C. (2021). AiR: An Augmented Reality Application for Visualizing Air Pollution. *IEEE Visualization Conference (VIS) 2021*, 146-150.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med, 6*(7).

Montello, D. R. (2018). *Handbook of behavioral and cognitive geography.* Cheltenham, UK; Northampton, MA, USA: Edward Elgar Publishing.

Mouratidis, K. (2021). How COVID-19 reshaped quality of life in cities: A synthesis and implications for urban planning. *Land Use Policy, 111*, 105772.

Mouratidis, K., Ettema, D., & Næss, P. (2019). Urban form, travel behavior, and travel satisfaction. *Transportation Research Part A: Policy and Practice, 129*, 306-320.

Mueller, N., Rojas-Rueda, D., Basagana, X., Cirach, M., Cole-Hunter, T., Dadvand, P., . . . Nieuwenhuijsen, M. (2017). Urban and Transport Planning Related Exposures and Mortality: A Health Impact Assessment for Cities. *Environmental Health Perspectives, 125*(1), 89-96.

Mytton, O. T., Panter, J., & Ogilvie, D. (2016). Longitudinal associations of active commuting with wellbeing and sickness absence. *Preventive Medicine, 84*, 19-26.

Nared, J. (2020). Participatory transport planning: The experience of eight european metropolitan regions. In J. Nared & D. Bole (Eds.), *Participatory Research and Planning in Practice. The Urban Book Series* (pp. 13-29), Cham: Springer.

Nieuwenhuijsen, M. (2016). Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. *Environmental Health, 15 Suppl 1*, 38.

Nieuwenhuijsen, M., & Khreis, H. (2019). Urban and Transport Planning, Environment and Health. In M. Nieuwenhuijsen & H. Khreis (Eds.), *Integrating Human Health into Urban and Transport Planning: A Framework* (pp. 3-16). Cham: Springer International Publishing.

Noel, C., Vanroelen, C., & Gadeyne, S. (2021). Qualitative research about public health risk perceptions on ambient air pollution. A review study. *SSM - Population Health, 15*, 100879.

Nordbakke, S., & Schwanen, T. (2013). Well-being and Mobility: A Theoretical Framework and Literature Review Focusing on Older People. *Mobilities, 9*(1), 104-129.

Okokon, E. O., Turunen, A. W., Ung-Lanki, S., Vartiainen, A.-K., Tiittanen, P., & Lanki, T. (2015). Road-traffic noise: annoyance, risk perception, and noise sensitivity in the Finnish adult population. *International Journal of Environmental Research and Public Health, 12*(6), 5712-5734.

Okokon, E. O., Yli-Tuomi, T., Turunen, A. W., Taimisto, P., Pennanen, A., Vouitsis, I., . . . Lanki, T. (2017). Particulates and noise exposure during bicycle, bus and car commuting: A study in three European cities. *Environmental Research, 154*, 181-189.

Orru, K., Nordin, S., Harzia, H., & Orru, H. (2018). The role of perceived air pollution and health risk perception in health symptoms and disease: a population-based study combined with modelled levels of PM10. *International Archives of Occupational and Environmental Health, 91*(5), 581-589.

Pánek, J. (2019). Mapping citizens' emotions: participatory planning support system in Olomouc, Czech Republic. *Journal of Maps, 15*(1), 8-12.

Park, Y. M. (2020). Assessing personal exposure to traffic-related air pollution using individual travel-activity diary data and an on-road source air dispersion model. *Health & Place, 63*, 102351.

Plotnikoff, R. C., & Trinh, L. (2010). Protection motivation theory: is this a worthwhile theory for physical activity promotion? *Exercise and Sport Sciences Review, 38*(2), 91-98.

Pooley, C. G., Horton, D., Scheldeman, G., Mullen, C., Jones, T., Tight, M., Jopson, A. & Chisholm, A. (2013). Policies for promoting walking and cycling in England: A view from the street. *Transport Policy, 27*, 66-72.

Prentice-Dunn, S., & Rogers, R. W. (1986). Protection Motivation Theory and preventive health: beyond the Health Belief Model. *Health Education Research, 1*(3), 153-161.

Ramos, C. A., Wolterbeek, H. T., & Almeida, S. M. (2016). Air pollutant exposure and inhaled dose during urban commuting: a comparison between cycling and motorized modes. *Air Quality, Atmosphere and Health, 9*(8), 867-879.

Ravindra, K., Singh, T., Vardhan, S., Shrivastava, A., Singh, S., Kumar, P., & Mor, S. (2022). COVID-19 pandemic: What can we learn for better air quality and human health? *Journal of Infection and Public Health, 15*(2), 187-198.

Reardon, L., & Abdallah, S. (2013). Well-being and Transport: Taking Stock and Looking Forward. *Transport Reviews*, *33*(6), 634-657.

Renn, O. (2014). Risikowahrnehmung in der Bevölkerung – Implikationen für das Sicherheitsempfinden. *Zeitschrift für Außen- und Sicherheitspolitik, 8*(1), 49-67.

Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, B. R. B., Pelling, M., Roberts, D.C., & Solecki, W. (2014). Urban areas. In C. B. Field, V. R. Barros, K. J. M. Dokken, M.D. Mastrandrea,, M. C. T.E. Bilir, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,, & a. L. L. W. P.R. Mastrandrea (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge.

Rogers, R. W. (1975). A Protection Motivation Theory of Fear Appeals and Attitude Change1. *The Journal of Psychology, 91*(1), 93-114.

Schäfer, S., & Everts, J. (2019). *Handbuch Praktiken und Raum: Humangeographie nach dem Practice Turn*. Bielefeld: transcript Verlag

Schatzki, T. R. (2001). Practice mind-ed orders. In T. R. Schatzki, K. Knorr-Cetina, & E. von Savigny (Eds.), *The Practice Turn in Contemporary Theory* (pp. 42-55). London: Routledge.

Schlink, U., & Ueberham, M. (2020). Perspectives of individual-worn sensors assessing personal environmental exposure. *Engineering*.

Schoenherr, J. R., & Thomson, R. (2020). Health Information Seeking Behaviour, Risk Communication, and Mobility During COVID-19. *IEEE International Symposium on Technology and Society (ISTAS),* 283-289.

Schulz, M. (2012). Quick and easy!? Fokusgruppen in der angewandten Sozialwissenschaft. In M. Schulz, B. Mack, & O. Renn (Eds.), *Fokusgruppen in der empirischen Sozialwissenschaft: Von der Konzeption bis zur Auswertung* (pp. 9-22). Wiesbaden: VS Verlag für Sozialwissenschaften.

Schulz, M., Mack, B., & Renn, O. (2012). *Fokusgruppen in der empirischen Sozialwissenschaft - Von der Konzeption bis zur Auswertung*. Wiesbaden: VS Verlag für Sozialwissenschaften | Springer Fachmedien.

SenUVK. (2017). *Mobilitat der Stadt. Berliner Verkehr in Zahlen 2017*. Senate Department for the Environment, Transport and Climate Protection. https://www.berlin.de/sen/uvk/verkehr/verkehrsdaten/zahlen-und-fakten/mobilitaet-der-stadt-berliner-verkehr-in-zahlen-2017/

SenUVK. (2019a). *Air Quality Plan for Berlin. 2nd Update*. Berlin: Senate Department for the Environment, Transport and Climate Protection, Pollution Control unit. https://www.berlin.de/sen/uvk/_assets/umwelt/luft/luftreinhaltung/luftreinhalteplan-2-fortschreibung/luftreinhalteplan_2019_en.pdf

SenUVK. (2019b). *Berlin wird leiser 2018 - Stellungnahmen zu den meistbewerteten Lärmorten (TOP 51)*. Senate Department for the Environment, Transport and Climate Protection . https://datenbox.stadt-berlin.de/filr/public-link/file-download/8a8ae3ab75bbb290017762d1eb8a1465/6454/-9176014905209661435/Anlage_5_LAP_Berlin_Stellungnahmen_TOP_51.pdf

SenUVK. (2021). *Radverkehrsplan des Landes Berlin (Radverkehrsplan Berlin – RVP)*. Senate Department for the Environment, Transport and Climate Protection. https://www.berlin.de/sen/uvk/_assets/verkehr/verkehrsplanung/radverkehr/radverkehrsplan/radverkehrsplan.pdf

SenUVK. (n.d.). *Berlin Mobility Act*. Senate Department for the Environment, Transport and Climate Protection. Retrieved from https://www.berlin.de/sen/uvk/en/traffic/transport-policy/berlin-mobility-act/

Sheller, M. (2018). Globalizing Networked Urbanism. Entanglements of Elite and Subaltern Mobilities. In M. Freudendal-Pedersen & S. Kesselring (Eds.), *Exploring networked urban mobilities : theories, concepts, ideas* (pp. 19-35). New York, London: Routledge, Taylor & Francis Group.

Sheller, M., & Urry, J. (2006). The New Mobilities Paradigm. *Environment and Planning A: Economy and Space, 38*(2), 207-226.

Shove, E., Pantzar, M., & Watson, M. (2012). *The Dynamics of Social Practice: Everyday Life and How it Changes*. Thousands Oaks, US: SAGE Publication.

Shrestha, R., Flacke, J., Martinez, J., & Van Maarseveen, M. (2016). Environmental health related socio-spatial inequalities: Identifying "hotspots" of environmental burdens and social vulnerability. *International Journal of Environmental Research and Public Health, 13*(7).

Sims, R., Schaeffer, F., Creutzig, X., Cruz-Núñez, M., D'Agosto, D., Dimitriu, M. J., . . . Tiwari, G. (2014). Transport. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge.

Snizek, B., Sick Nielsen, T. A., & Skov-Petersen, H. (2013). Mapping bicyclists' experiences in Copenhagen. *Journal of Transport Geography, 30*, 227-233.

Snyder, E. G., Watkins, T. H., Solomon, P. A., Thoma, E. D., Williams, R. W., Hagler, G. S. W., . . . Preuss, P. W. (2013). The Changing Paradigm of Air Pollution Monitoring. *Environmental Science & Technology, 47*(20), 11369-11377.

Spinney, J. (2016). A Place of Sense: A Kinaesthetic Ethnography of Cyclists on Mont Ventoux. *Environment and Planning D: Society and Space, 24*(5), 709-732. doi:10.1068/d66j

Stallen, P. J. (1999). A theoretical framework for environmental noise annoyance. *Noise and Health, 1*(3), 69-79.

Steinmetz-Wood, M., Pluye, P., & Ross, N. A. (2019). The planning and reporting of mixed methods studies on the built environment and health. *Preventive Medicine, 126*, 105752.

Stephan, C. (2019). *Living with floods : Social practices and transformations of flood management in Chiapas, Mexico*. Stuttgart: Franz Steiner Verlag

Sui, D. Z., Elwood, S., & Goodchild, M. (2013). *Crowdsourcing geographic knowledge : volunteered geographic information (VGI) in theory and practice.* Dordrecht: Springer.

Synek, S., & Koenigstorfer, J. (2019). Health effects from bicycle commuting to work: Insights from participants of the German company-bicycle leasing program. *Journal of Transport and Health, 15*.

Terpstra, T., & Lindell, M. K. (2013). Citizens' Perceptions of Flood Hazard Adjustments: An Application of the Protective Action Decision Model. *Environment and Behavior, 45*(8), 993-1018.

Tomsho, K. S., Schollaert, C., Aguilar, T., Bongiovanni, R., Alvarez, M., Scammell, M. K., & Adamkiewicz, G. (2019). A Mixed Methods Evaluation of Sharing Air Pollution Results with Study Participants via Report-Back Communication. *International Journal of Environmental Research and Public Health, 16*(21).

Travaglio, M., Yu, Y., Popovic, R., Selley, L., Leal, N. S., & Martins, L. M. (2021). Links between air pollution and COVID-19 in England. *Environmental Pollution, 268*, 115859.

Ueberham, M., & Schlink, U. (2018). Wearable sensors for multifactorial personal exposure measurements - A ranking study. *Environment International, 121*(1), 130-138.

Ueberham, M., Schlink, U., Dijst, M., & Weiland, U. (2019). Cyclists' Multiple Environmental Urban Exposures - Comparing Subjective and Objective Measurements. *Sustainability, 11*(5), 1412 .

Ueberham, M., Schmidt, F., & Schlink, U. (2018). Advanced Smartphone-Based Sensing with Open-Source Task Automation. *Sensors, 18*(8), 2456.

van Duppen, J., & Spierings, B. (2013). Retracing trajectories: the embodied experience of cycling, urban sensescapes and the commute between 'neighbourhood' and 'city' in Utrecht, NL. *Journal of Transport Geography, 30*, 234-243.

van Kamp, I., Klaeboe, R., Brown, L., & Lercher, P. (2016). Soundscapes, Human Restoration, and Quality of Life. In J. Kang & B. Schulte-Fortkamp (Eds.), *Soundscape and the Built Environment* (Vol. 1). Boca Raton: CRC Press.

van Wee, B. V., & Banister, D. (2016). How to Write a Literature Review Paper? *Transport Reviews, 36*(2), 278-288.

van Wee, B., & Ettema, D. (2016). Travel behaviour and health: A conceptual model and research agenda. *Journal of Transport & Health, 3*(3), 240-248.

Vasilikou, C. (2016). *Sensory Navigation in the City Centre. Perceptual paths, sense walks and interactive atmospheres.* Proceedings of 3rd International Congress on Ambiances. Septembre 2016, Volos, Greece, 559 - 564. hal-01414151.

Vasilikou, C., & Nikolopoulou, M. (2020). Outdoor thermal comfort for pedestrians in movement: thermal walks in complex urban morphology. *International Journal of Biometeorology, 64*(2), 277-291.

Verbeek, T. (2018). The relation between objective and subjective exposure to traffic noise around two suburban highway viaducts in Ghent: lessons for urban environmental policy. *Local Environment, 23*(4), 448-467.

Vollmer, R., & Gruschwitz, D. (2019). *Mobility in Germany – short report.* Retrieved from Bonn, Berlin: www.mobilitaet-in-deutschland.de

Weichhart, P. (2018). *Entwicklungslinien der Sozialgeographie : von Hans Bobek bis Benno Werlen* (2. ed.). Stuttgart : Franz Steiner Verlag.

Wenzl, C., Werner, C., Molitor, K., Hornung, M., Rominger, S., & Faller, F. (2019). Soziale Praktiken in der Forschungspraxis – empirisch forschen mit Schatzkis site ontology. In S. Susann & E. Jonathan (Eds.), *Handbuch Praktiken und Raum: Humangeographie nach dem Practice Turn* (pp. 341-360). Bielefeld: transcript Verlag.

WHO (2011). *Burden of disease from environmental noise: quantification of healthy life years lost in Europe*. World health Organization Regional Office for Europe and JRC European Commission. https://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf

WHO (2018). *Environmental Noise Guidlines for the European Region.* World Health Organization Regional Office for Europe. https://apps.who.int/iris/rest/bitstreams/1175318/retrieve

Wilde, M. (2013). *Mobilität und Alltag: Einblicke in die Mobilitätspraxis älterer Menschen auf dem Land*. Wiesbaden: Springer VS.

Wilde, M., Gather, M., Neiberger, C. & Scheiner, J. (2017). *Verkehr und Mobilität zwischen Alltagspraxis und Planungstheorie. Ökologische und soziale Perspektiven*. Wiesbaden: Springer VS.

Wilde, M., & Klinger, T. (2017). Integrierte Mobilitäts- und Verkehrsforschung: zwischen Lebenspraxis und Planungstheorie. In M. Wilde, M. Gather, C. Neiberger, & J. Scheiner (Eds.), *Verkehr und Mobilität zwischen Alltagspraxis und Planungsheorie. Ökologische und soziale Perspektive* (pp. 5-19). Wiesbaden: Springer VS.

Appendices

Appendix A

Further publications related to this thesis

Authors	Year	Title	Journal
A. M. Becker, **H. Marquart,** T. Masson, C. Helbig and U. Schlink	2021	Impacts of Personalized Sensor Feedback Regarding Exposure to Environmental Stressors	Current Pollution Reports Vol. 7 Issue 4 Pages 579-593 https://doi.org/10.1007/s40726-021-00209-0

Abstract:
Feedback on personal exposure to air pollution, noise or extreme temperatures through wearable sensors or sensors installed at home or in the workplace can offer information that might motivate behaviours to mitigate exposure. As personal measurement devices are becoming increasingly accessible, it is important to evaluate the effects of such sensors on human perception and behaviour. We conducted a systematic literature research and identified 33 studies, analysing the effects of personal feedback on air pollution, noise and temperatures. Feedback was given through reports including different forms of visualization, in-person or over the telephone, or directly on the sensor or through a phone app. The exposure feedback led to behaviour changes particularly for noise and temperature feedback while findings on behaviour adaptation to avoid air pollution were mixed. Most studies reported increased awareness and knowledge from receiving exposure feedback. Many participants in studies on air pollution reported low levels of self-efficacy regarding exposure mitigation. For a better understanding of the effects of personal exposure feedback, more studies are required, particularly providing feedback from wearable sensors measuring outdoor air pollution, noise and temperature.

Authors	Year	Title	Journal
H. Marquart, J. Schicketanz	2022	Experiences of safe and healthy walking and cycling in urban areas: The benefits of mobile methods for citizen-adapted urban planning	Transportation Research Procedia 2022 Vol. 60 Pages 290-297 https://doi.org/10.1016/j.trpro.2021.12.038

Abstract:
Walking and cycling promotes physical activity and mental health. In many European cities, walking and cycling has increased and is a key part of transport planning. However, many cyclists and pedestrians still perceive themselves as neglected road users, face air pollutants, noise and fear travel injuries. Children are in particular vulnerable. The aim of this study is to present mobile interview methods ("go-/ride-alongs") for promoting safe and healthy cycling/walking in urban transport planning. We present two studies from Berlin (a) and Leipzig (b), Germany. We conducted go-/ride-alongs with cyclists and pedestrians on (a) their commute home from work and (b) children on their way to school. We accompanied them and investigated how they experience commuting, the environment and discover ad-hoc situative behavior. We discuss our findings and transfer our knowledge gained through the mobile method into transport planning strategies. Safety is most often mentioned by all interviewees. Our studies show a high importance of in-situ/ad-hoc experiences for travel behavior, which can be examined with an interviewer accompanying. Our methods encourage interviewees to describe past experiences, how they shape their behavior or factors supporting/hindering active travel. We consider mobile methods important for exploring mobility and successful when complemented by participatory methods and instruments (e.g., participatory mapping, smartphone-apps, group walks). Therefore, the voice of vulnerable road users can be strengthened. In a next step individual local experiences and community knowledge could be incorporated in urban transport planning to improve active travel.

Appendix B

Interview guideline of the go- and ride-alongs

(translated from German into English by the author)

A. Mobility practices and route choices
   - 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 go- and ride-along, 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 you 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. Directly followed by noise.
   - 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.

F. *Ad-hoc questions*

Appendix C

Interview guideline of the focus groups

(translated from German into English by the author)

Arrival and Introduction		**Tools**

Welcome, Agenda, Procedure	1. Welcome, organizational issues
	2. Introduction and basic rules:
	    a. Short explanation about the research project and the aims of the focus group discussion
	    b. Clarifying basic rules of focus groups: no false/right answers, all opinions and experiences are relevant and valuable, talk about your own point of view/experiences, its about personal opinions and subjective experiences
	3. Agenda (questions?)
		Powerpoint presentation

Getting to know each other and get familiar with the situation	To get to know each other, I would like to invite you to give a short introduction to the others about yourself: • Name, background • If I was a specific mode of transport, I would be a… (e.g. bicycle, train, car,…) • If I imagine my perfect commuting trip to work, it would consist of…	Powerpoint presentation
1. Topic: Exchange experiences following the go-/ride-alongs *(based on PMT (threat appraisal and coping appraisal))*		
To get started: Sharing the perceived personal exposure with others Evaluating perceived severity and vulnerability of air pollution and noise	To get started: 1. Take a look at the pinboard. If you think of the last trips (to work), that you have tracked with the MovingLab tracking App following the go-/ride-along, how much did you feel disturbed or annoyed from traffic related **noise**? *Participants are asked to take a pin and place it on the pin board* *Scale from 1-10 supported by the scale of - Extremely - Strongly - Moderately - Somewhat - Not at all?* 2. Take a look at the pinboard. If you think of the last trips (to work), that you have tracked with the MovingLab tracking App following the go-/ride-along, how much did you feel disturbed or annoyed from traffic related **air pollution**? *Participants are asked to take a pin and place it on the pin board* *Scale from 1-10 supported by the scale of - Extremely - Strongly - Moderately - Somewhat - Not at all?* 3. Take a look at the pinboard. If you think of the last trips (to work), that you have tracked with the MovingLab tracking App following the go-/ride-along, how much did you feel that your **health** was impacted by these stressors? *Participants are asked to take a pin and place it on the pin board* *Scale from 1-10 supported by the scale of - Extremely - Strongly - Moderately - Somewhat - Not at all?* ➔ We will leave the pin board here so that you can look at it later on throughout the focus groups.	Pin board on which every participant can pinpoint a pin on the respective scales (online focus group it was done online) Note: they did not know the results of their exposure measurements at that time.

Sharing experiences of the go-/ride-alongs	4. Now, please think of the go-/ride-alongs we have undertaken together and remember the time following the go-/ride-alongs. The following beginnings of the sentences can guide you: I am happy that I **participated** (in the go-/ride along), because… My biggest **eye opener** was (when I/we)… It made me **worry or fear**, that… I find it **positive**, that….	Powerpoint slide with the beginnings of the sentences for guidance
MovingLab tracking route choices	5. Now let's think of the routes you have chosen when you did the MovingLab tracking following the go-/ride-alongs. What **did you change** or which **alternative routes** did you try out? Did you **perceive something different** on these routes?	Stand around the MovingLab table, where the tracked routes are visible on the screen and can be zoomed in and out (1. Focus group), tracked routes shown as a picture via PowerPoint (2. and 3. Focus group)
2. Topic: Feedback about measured air pollution and noise exposure *(based on EHL and PMT: Self-efficacy and response efficacy)*		
Participants receive a small brochure in which their measured peak exposure along the routes is presented as well as some explanation and further information	(5 minutes to read through the brochure) *Short input to air pollution and noise measurements in the city.* If you take a look at the exposure measurements: What was **surprising**? What makes you **worry/scared**? What was **reassuring** or **positive**?	Feedback brochure Powerpoint presentation with peaks in exposure measurements
MovingLab tracking routes	If we now follow up on what was surprising/concerning/positive/…: Let's take a look the routes you have taken during the MovingLab tracking (showing tracked routes in the MovingLab table or on the screen): What would you **change regarding your routes**/what could you do to effectively protect yourself? What are you **willing to do/change**? What **protective measures** would you include in our trip? Which of these behavioural changes will you undertake in the **long-term**?	Visual input: Showing some pictures undertaken during the go-/ride-alongs (1. focus group: discussion done on the

		MovingLab table)
3. Topic: Information and communication requirements *(based on EHL)*		
Information and communication options	Information is important to support healthy mobility choices. Let's now take a look at some possibilities to be informed about healthy mobility. *(showing different options of exposure information, e.g. signs, mobility apps, media, other examples)* Which **information** do you usually consult for your daily routes? What would you **like to know** in the future regarding **particulate matter, noise or health burdens**? What would you **like to know** in the future **regarding healthier route planning**? How should this information be **communicated or presented** to you? Everything is possible! Please let your creativity run free.	Examples (with pictures) of communication and information options regarding air pollution and noise in the city via Powerpoint presentation

Appendix D
Codesystem go- and ride-alongs

Code and Sub-codes	Number of mentions in the transcripts
1 Protective practices	
1.1 Supress/Ignore exposure	10
1.3 Pause to "calm down"	5
1.4 Hold breath/cover nose	6
1.5 Increased distance (to cars/emitter)	10
1.6 Increase speed (avoid areas)	11
1.7 Violate traffic rules	34
1.8 "Hidden path"	38
2 Sensory awareness	
2.1 related to perceived sounds	
2.1.1 Noise	49
2.1.2 Quietness	40
2.1.3 Positive sounds (people talking)	2
2.1.4 Positive sounds (related to memories)	1
2.1.5 Positive sounds (musicians playing music)	4
2.2 related to perceived air/smells	
2.2.2 Fresh air	9
2.2.3 Good smell (nature/water)	7
2.2.4 Good smell (related to memories)	1
2.2.5 Neutral smells	2
2.2.6 Noticeable air pollution	42
2.3 related to visual experiences	
2.3.1 Social aspects/community feeling	19
2.3.2 Dirt / dark areas	8
2.3.3 Unaesthetic urban structures	8
2.3.4 Vast view	10
2.3.5 Places/situations of interest/curiosity	19
2.3.6 Observe people	18
2.3.7 Vegetation/Water	49
2.3.8 Entertainment (Shops/Cafés/etc.)	11
2.3.9 Urban aesthetics	24
2.4 Related to physical health	
2.4.1 Unhealthy	7

2.4.2 Healthy	10
2.4.3 Body tension	10
2.4.4 Safe feeling (traffic injuries)	14
2.4.5 Safe feeling (social safety)	2
2.4.6 Unsafe feeling (social safety)	6
2.4.6 Unsafe feeling (traffic injuries)	27
2.5 Affective/emotional experiences	
2.5.1 Pleasant	
2.5.1.1 Relaxing	57
2.5.1.2 Attractive	44
2.5.1.3 Pleasant	93
2.5.2 Unpleasant	
2.5.2.1 Unpleasant	60
2.5.2.2 Stressful	47
2.5.2.3 Unattractive	8
3 Relevant observed built environment/ important infrastructure / traffic situations	0
3.1 Good walking infrastructure	2
3.2 Subway/Tram/Train	10
3.3 Train station/hall	7
3.4 Lights	1
3.5 Freeway	6
3.6 Bus stop	2
3.7 Parking cars	16
3.8 Bad/missing cycling infrastructure	17
3.9 Cycling infrastructure	16
3.10 No/Few cars	41
3.11 Crowded areas (cyclists)	14
3.12 Crowded areas (cars)	47
3.13 Crowded areas (people)	17
3.14 Intersection	21
3.15 Underpass	6
3.16 Cemetery	3
3.17 Pop-up Bike Lane	5
3.18 Subway (tunnel)	1
3.19 (Smaller) side roads	39
3.20 Water	11
3.21 Greenery/Vegetation	51

3.22 Busses	4
3.23 Tracks	1
3.24 Cobblestone / bumpy road	12
3.25 School	1
3.26 Construction site	15
3.27 Traffic lights	45
4 Measured air pollution (relative to respective route)	
7 - comparably extremely high	52
6 - comparably very high	38
5 - comparably high	41
4 - mean	41
3 - comparably low	39
2 - comparably very low	39
1 - comparably extremely low	33
5 Measured noise (median of 10 sec.)	
46-50 dB(A)	4
51-55 dB(A)	12
56-60 dB(A)	33
61-65 dB(A)	76
66-70 dB(A)	75
71-75 dB(A)	56
76-80 dB(A)	29
81-85 dB(A)	4

Appendix E
Codesystem focus groups

Code and Sub-codes	Number of mentions in the transcripts
1 Information source & communication of risks	
1.1 Information denial	
1.1.1 Lack of accuracy	3
1.1.2 Lack of understanding	12
1.1.3 Information overdose	5
1.1.4 "Why should I change?"	7
1.1.5 Don't want to be informed	11
1.2 Supporting creation and community change	
1.2.1 Political action instead of informing	8
1.2.2 Informing others in community / increased desire to become an activist or support activism	12
1.3 Supporting application, analysis and evaluation	
1.3.1 Pollution integrated in weather apps	3
1.3.2 Healthiest route navigation	10
1.3.3 Map with pollution information	5
1.3.4 Info about highly trafficked roads	4
1.3.5 Alerts	2
1.4 Supporting recognition & understanding	
1.4.1 General Information signs	3
1.4.2 Governmental sources	1
1.4.3 Translating measurement data into something relatable	8
1.4.4 Informing polluters	5
2 Protection motivation as a result of the go-/ride-along, measurements and GPS-tracking	
2.1 Response-efficacy – does/can protective practices really improve commute	
2.1.1 Political/social trustworthiness	11
2.1.2 Practice improves health/wellbeing	8
2.1.3Practice does not improve health/wellbeing	10
2.1.4 Refuse/Useless to change routes/practices	16
2.2 Self-efficacy - am I able to conduct protective practices	
2.2.1 Mode changes	2
2.2.2 Increase distance to emitter	3

2.2.3 Route changes	8
2.2.4 Cover nose / cover ear (headphones) / hold breath	9
2.2.5 Other decisive factors	14
2.2.6 Suppressing exposure	5
2.2.7 Feeling of powerlessness	19
2.3 Perceived vulnerability - how one feels at risk	
2.3.1 Do not feel at risk/perceive air pollution/noise	15
2.3.2 Sensory awareness and physiological effects	20
2.4 Perceived severity - making sense of the risks	
2.4.1 Information increases perceived severity	24
2.4.2 Information does not increase perceived severity	5