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

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ABSTRACT

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

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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

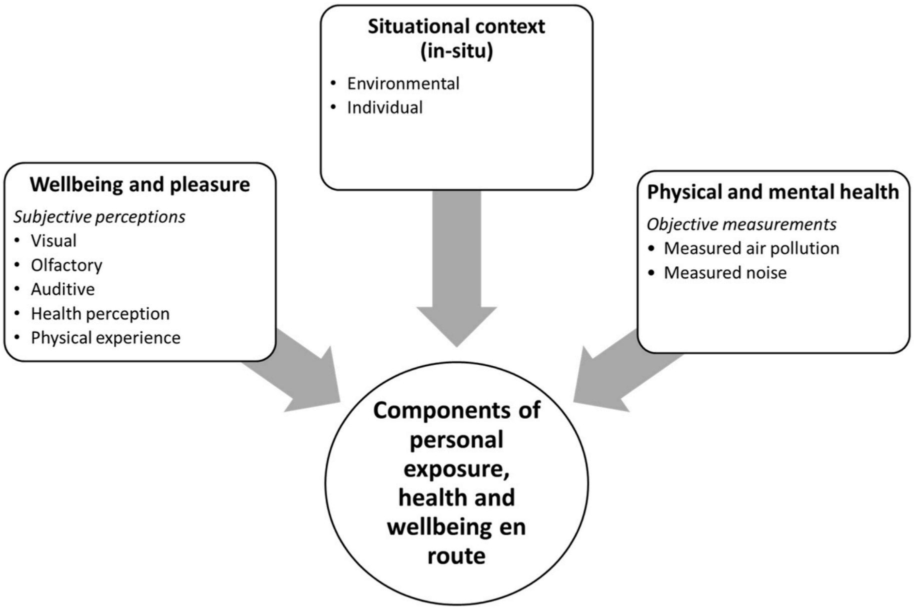

Fig. 1. Conceptual framework (based on Marquart et al., 2021): Interaction of personal exposure, health and wellbeing en route. Physical/mental health impacts from measurable air pollution and noise (state-of-the-art research on exposure), situational context (i.e., in-situ environmental situation and 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.

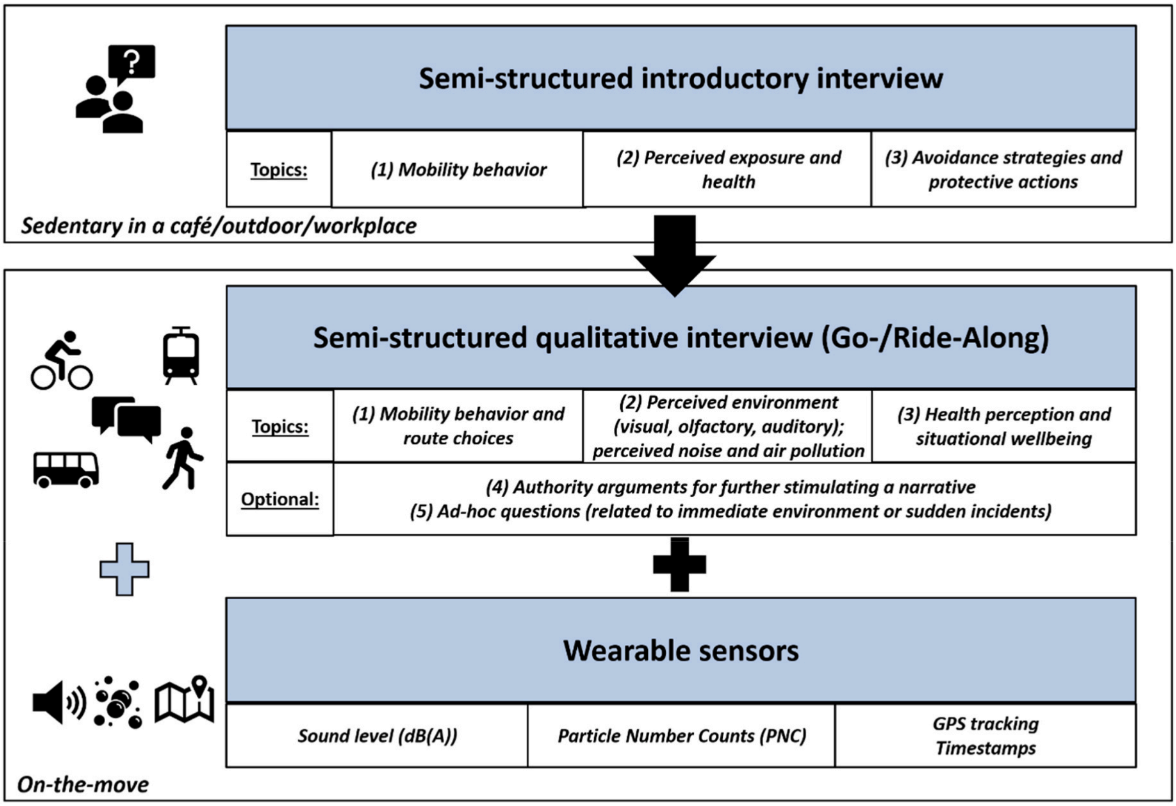

Fig. 2. Study design.

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		

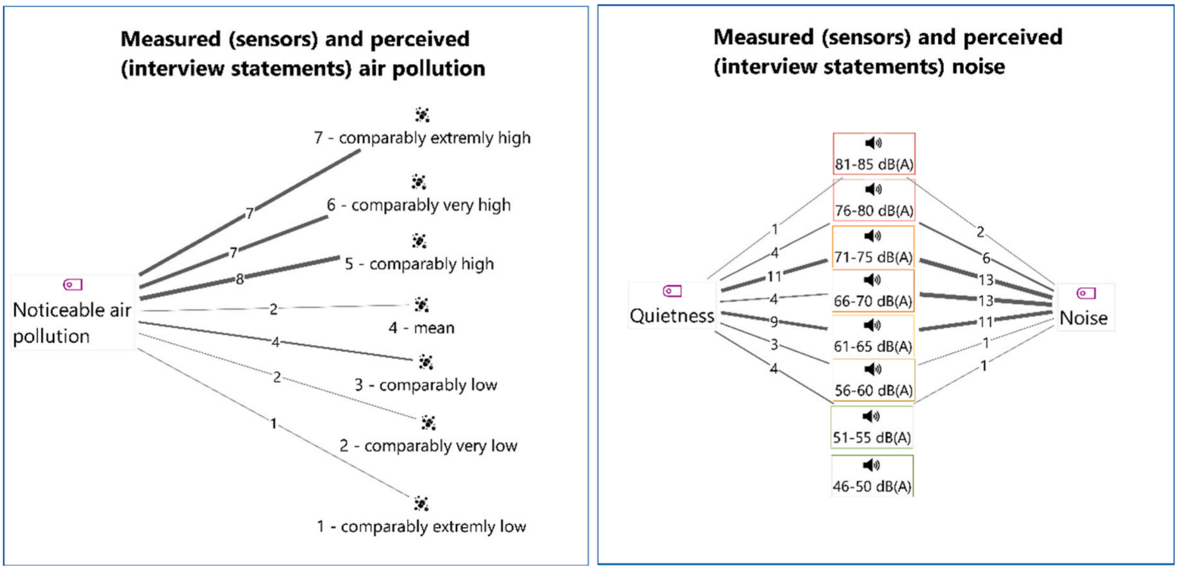

Fig. 3. Left: Comparing measured (sensors) air pollution data with perceived air pollution (interview statements on momentary noticeable air pollution). Right: Comparing measured (sensors) noise data with perceived noise/quietness (interview statements on momentary perceived noise/quietness).

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.

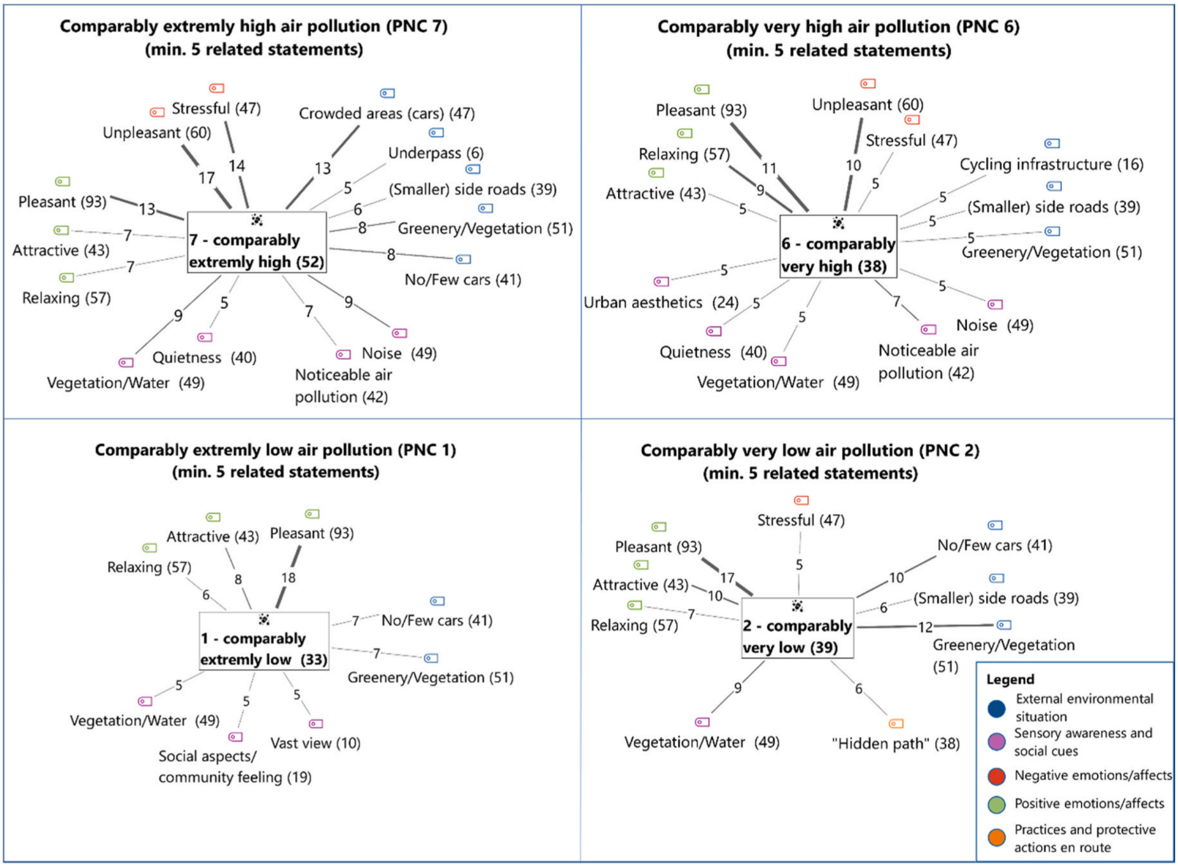

Fig. 4. Coded interview statements ("codes") during extremely high/very high and extremely low/very low measured particle number counts (for better visualization, only codes which were found at least 5 times or more are shown). The numbers in brackets represent the total number of each code as retrieved 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).

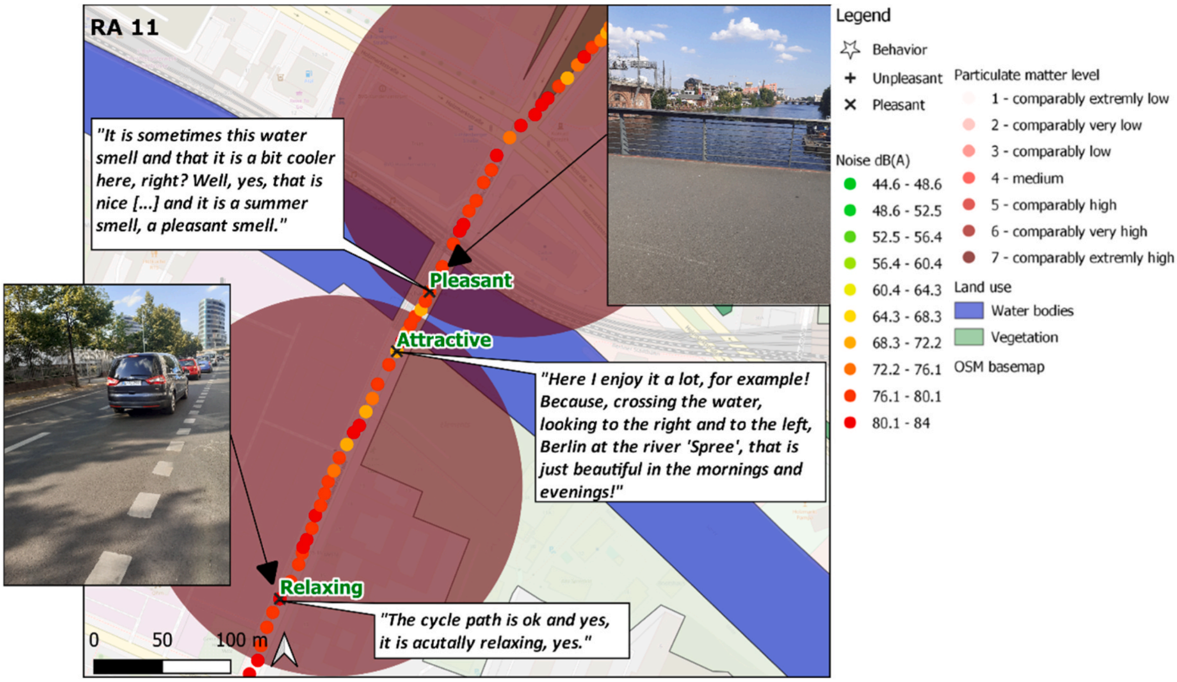

Fig. 5. Differences in perceived and measured exposure and the importance of the surrounding environment, i.e., bodies of water (RA11).[3]

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

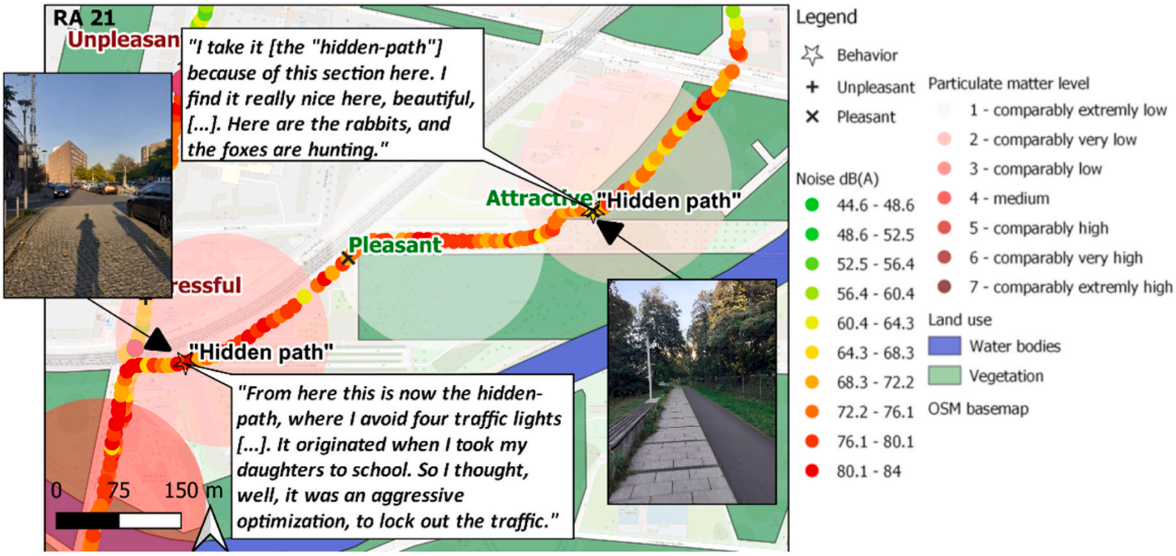

Fig. 7. Example of "hidden paths", made by Ride-Along 21. The PNC level in the hidden paths was comparably extremely low, and the interviewee perceived it as pleasant and attractive. The noise measurements should be interpreted with caution, because the cobblestones, leaves rustling or wind may have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

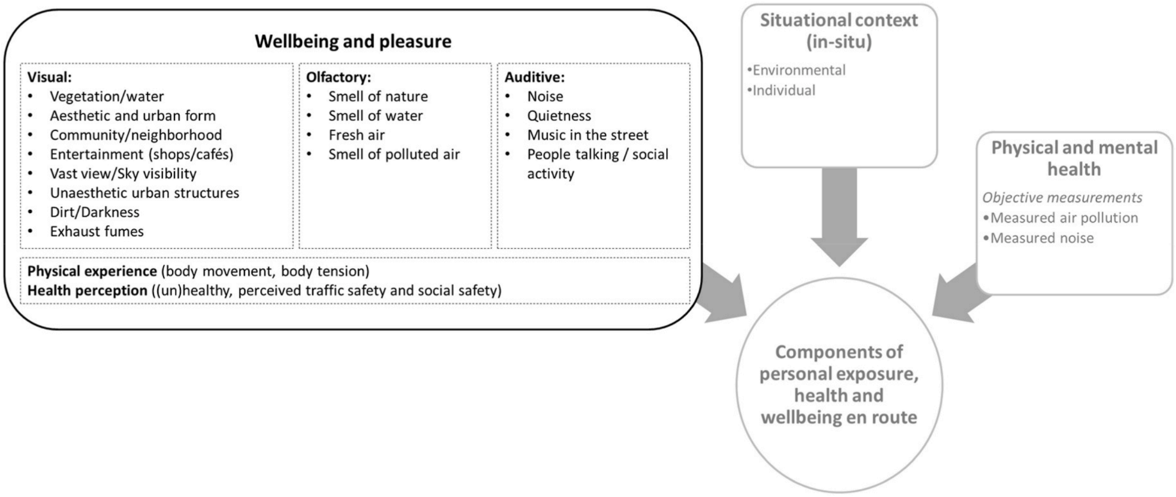

Fig. 8. Extended conceptual framework for personal exposure, health and wellbeing en route (based on Fig. 1), enriched with the results obtained in the present study.

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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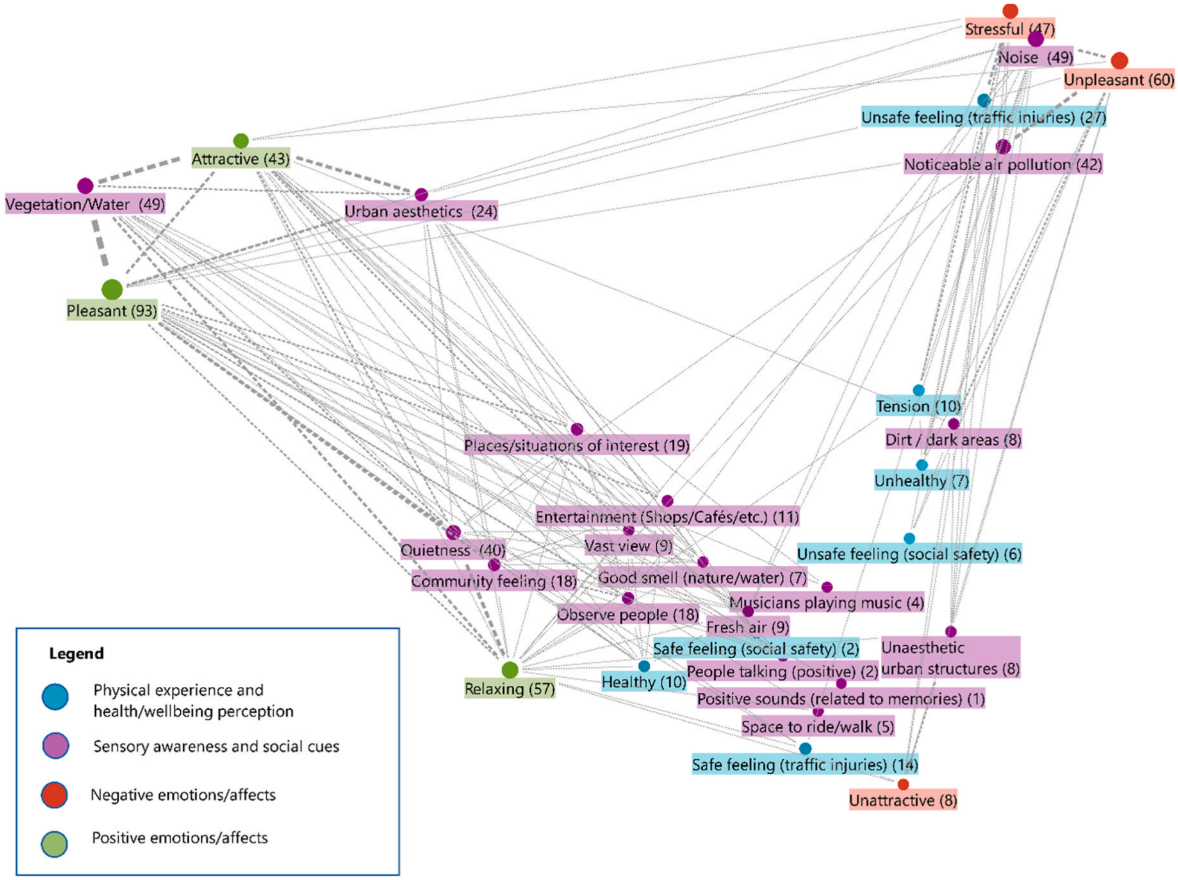
Appendix A

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.



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