HOW TO ASSESS THE NEEDS OF VULNERABLE POPULATION GROUPS TOWARDS HEAT-SENSITIVE ROUTING? AN EVIDENCE-BASED AND PRACTICAL APPROACH TO REDUCING URBAN HEAT STRESS

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With 7 figures, 2 tables and 3 appendices
Received 17 August 2023 · Accepted 23 February 2024

Summary: Heat poses a significant risk to human health, particularly for vulnerable populations, such as pregnant women, older individuals, young children and people with pre-existing medical conditions. In view of this, we formulated a heat stress-avoidant routing approach in Heidelberg, Germany, to ensure mobility and support day-to-day activities in urban areas during heat events. Although the primary focus is on pedestrians, it is also applicable to cyclists. To obtain a nuanced understanding of the needs and demands of the wider population, especially vulnerable groups, and to address the challenge of reducing urban heat stress, we used an inter- and transdisciplinary approach. The needs of vulnerable groups, the public, and the city administration were identified through participatory methods and various tools, including interactive city walks. Solution approaches and adaptation measures to prevent heat stress were evaluated and integrated into the development of a heat-avoiding route service through a co-design process. The findings comprise the identification of perceived hotspots for heat (such as large public spaces in the city centre with low shading levels), the determination of commonly reported symptoms resulting from severe heat (e.g., fatigue or lack of concentration), and the assessment of heat adaptation measures that were rated positively, including remaining in the shade and delaying errands. Additionally, we analysed and distinguished between individual and community adaptation strategies. Overall, many respondents did not accurately perceive the risk of heat stress in hot weather, despite severe limitations. As a result, the heat-sensitive routing service (available in prototype form during publication) that has been created serves as a readily available and accessible source of assistance to combat the effects of heat stress in individuals' daily lives during periods of intense heat. The findings served as input for the calibration of heat stress-avoidant routing and supported the development of local heat protection plans without investing in large-scale adaptation of the built environment. It is crucial to involve the population, particularly vulnerable groups, in the development of the tool to ensure it meets their needs. This study employed a transdisciplinary multi-method approach, which considers practical framework conditions by involving the city administration.

Keywords: Climatic change, urban climate, urban planning, GIS, applied geography, Baden-Wuerttemberg

1 Introduction

Anthropogenic climate change is leading to an increase in the frequency, duration and intensity of heat waves (IPCC 2022, Rüegg 2019, Wouters et al. 2017) and has become a major concern for several regions around the world (Rosenzweig et al. 2015, Bulkeley et al. 2009). While some of the effects of climate change have already occurred, severe mitigation efforts cannot reverse them quickly. In urban areas, heat stress is additionally intensified by their characteristics and the resulting heat island effect (Bulkeley et al. 2009, Rosenzweig et al. 2015, Stone et al. 2010). Heat is a burden on the human body that can lead to health problems and heat-related mortality (Bambrick et al. 2011, European Environment Agency 2022, Schuster et al. 2017, The Lancet 2021). Vulnerable groups such as pregnant women, young children, older people and the sick are particularly affected (European Environment Agency 2022, The Lancet 2021, Harlan & Ruddell 2011). In addition, the quality of life and well-being is greatly reduced in the absence of thermal adaptation measures in public spaces (European Environment Agency 2016, Foshag et al. 2020, Lafortezza et al. 2009, Andersson et al. 2019). To promote health and maintain the viability of cities, everyday life and mobility need to be supported and ensured even in extreme temperatures (Hatvani-Kovacs et al. 2016, Ketterer & Matzarakis 2014, Lindberg et al. 2016, Matthews et al. 2017). Previous approaches often focus on urban planning measures (Bulkeley et al. 2009) or produce scientific results that are difficult or significantly delayed to implement in practice. However, the extreme events that are already occurring today require immediate action, both at the in-

 https://doi.org/10.3112/erdkunde.2024.01.01 ISSN 2702-5985 (Online)

dividual level and at the urban planning level, without the need for long-term planning or substantial measures in the built environment. Our approach aimed to bridge this gap by actively engaging with local communities. This is in addition to structural adjustments that are generally resource-intensive and subject to various political and regulatory framework conditions. Heat action plans incorporate measures with varying time horizons. Immediate or rapid actions that can be taken include constructing drinking water fountains, opening cool buildings like churches during extreme heat peaks, and mapping public green and recreational areas. Such measures are currently being implemented in several cities, including Heidelberg, Germany. Heat-avoiding routing is a fast solution that individuals can use to prevent heat-related stress in urban areas. It is effective even when no major structural adaptation measures have been taken to the urban infrastructure and is constantly improving with their implementation due to the increasing availability of low-heat routes.

The study aimed to answer the research question: How can the needs and conditions of vulnerable populations and practitioners be captured in a differentiated way for a heat avoidance routing tool?

In detail the article focuses on representing local heat stress, its small-scale spatial differentiation, and assessing the situation by different population groups, their associated needs, and the approach in which this can be taken into account in the development of the routing prototype. Both quantitative and qualitative methods were employed, as detailed in section three. The results section presents the various findings and factors that must be considered when developing the heat-avoiding routing tool that integrates both individual needs and practical conditions. The discussion evaluates the details of the study, including the analysis of differences between the study groups and the suitability of the method set itself.

The publication forms part of the HEAL (Heat Adaptation for Vulnerable Population Groups) research project, which seeks to provide heat adaptation measures for vulnerable population groups in Heidelberg. The project's main focus is the heat-avoiding route service, which is currently in prototype. This publication presents the participatory development and interim evaluation of the completed routing prototype. It focuses on the basic considerations, assessments, and data generated through the multi-method set for the prototype's development and design. The publication concludes with preliminary results from user testing with both the general population and vulnerable individuals. The routing tool is currently undergoing iterative adaptation until finalisation and presentation to the public.

2 Heat adaptation and vulnerability to health impacts

Anthropogenic climate change is leading to an overall increase in global mean temperature, with significant regional differences (IPCC 2022, Wouters et al. 2017). While rural areas, which are also affected by general warming and temporary overheating, experience cooling by radiation during the night, urban areas are exposed to permanently higher temperatures than their surroundings due to their higher degree of sealing and building structure (urban heat island effect) (Wouters et al. 2017, Schuster et al. 2017, Zhao et al. 2018). This effect is further amplified by climate change (Rüegg 2019). In addition, climate change is leading to an increase in the duration, intensity and frequency of heat waves (Rüegg 2019, Russo et al. 2015, Christidis et al. 2014). This development poses an increased health risk for (urban) populations (European Environment Agency 2022, Harlan & Ruddell 2011, The Lancet 2021). Data showed that heat-related morbidity and mortality have increased in recent decades, and that extreme heat events are also associated with increasing numbers of heat-related illnesses and deaths (Ebi et al. 2021, Matthews et al. 2017, Mora et al. 2017, Donato et al. 2015, Winklmayr et al. 2022). About 37 % of heat-related deaths worldwide can be attributed to climate change between 1991 and 2018, according to data from 43 countries (Vicedo-Cabrera et al. 2021). At the same time, the world is becoming increasingly urbanised, with more than 60 % of the world's population expected to live in cities by 2030 (United Nations 2019).

Heat events with high outdoor temperatures during the day and little cooling at night put a strain on the human organism. Even small increases in ambient temperature or humidity have a direct impact on human health, leading to dehydration, cardiovascular stress, physical and mental impairment and heat stroke (Ebi et al. 2021, Reid et al. 2012, Ahima 2020, Périard et al. 2021). Small deviations of around 1.5 °C from the body's core temperature (37 °C (± 0.5 °C)) can significantly affect physiological functions and lead to a significant reduction in physical and mental performance (European Environment Agency 2022). In most cases, direct heat-related adverse health effects are the result of inadequate thermoregulatory capacity (Périard et al. 2021, Ahima 2020). Several groups are more vulnerable to the climatic risk factor of heat than the general population (Reid et al. 2012, Pillich 2018, Ebi et al. 2021). We incorporated four groups: older people, those with pre-existing conditions such as cardiovascular disease, young children, and pregnant women (Reid et al. 2012, Pillich 2018, Ebi et al. 2021). Pregnant women merit special attention as they are typically healthy young women who may suddenly face heightened vulnerability during pregnancy. The heightened vulnerability of certain groups is also due, for example, to the use of certain medications (e.g., antidepressants) that are more commonly used in these groups (older people, people with physical or mental illnesses). These medications can impact thermoregulation or alter their efficacy by increasing, decreasing, or modifying it (Stöllberger et al. 2009). In addition, some groups of people (e.g., Older people and young people in their teens and twenties) tend to misjudge their own vulnerability and underestimate the risk of heat-related health damage or impairment (Hatvani-Kovacs et al. 2016, Cvitanovic et al. 2019, Sandholz et al. 2021). Risk assessment is an important factor influencing individual behaviour, and inaccurate assessment can be an obstacle to successful prevention or heat adaptation measures. In addition, there is an uneven distribution of opportunities and resources for active heat protection among the population (Sandholz et al. 2021, Osberghaus & Abeling 2022).

Sustainable urban planning aims at reducing the degree of sealing, increasing the amount of green spaces and shading. It can therefore have a positive impact on the urban microclimate and the well-being of the urban population (Lafortezza et al. 2009, Andersson et al. 2019, European Environment Agency 2022). Adapted planning and modification of the local environment can have a supportive effect and promote the application of preventive behavioural measures by individuals. In addition, the development and implementation of heat action plans is an important task for cities (Ketterer & Matzarakis 2014, Lindberg et al. 2016). For example, it is proposed to install drinking water dispensers in public places to prevent dehydration and promote health during heat events (European Environment Agency 2022).

The rapidly growing threat to human health and impairment of daily life from heat extremes underlines the need to adapt to increasing heat (Schuster et al. 2017). Urban adaptation measures mainly relate to increasing the proportion of green and blue infrastructure in urban areas. Green and water areas can positively modify the local microclimate through effects such as evaporative cooling. In addition, artificial shading of urban areas such as pedestrian zones has also become more common in recent years and has a major impact on cooling. (Colter et al. 2019, Garcia-Nevado et al 2020). Urban adaptation measures to reduce heat stress can support and facilitate individual heat adaptation strategies (Hatvani-Kovacs et al. 2016, Ketterer & Matzarakis 2014, Lafortezza et al. 2009, Gunawardena et al. 2017).

These factors also affect mobility patterns, such as prioritising green spaces and shaded routes. Communication and linking of these ‘cool places’, which are areas of well-being and recreation, can improve quality of life and prevent heat-related illnesses. This should be consistently expanded to accompany our developed routing tool. Furthermore, the routing approach highlights areas in Heidelberg that lack sufficient urban adaptation measures (areas where few low heat stress alternative routes can be generated by the model). In addition, the model can be used to generate heat stress maps or to assess the accessibility of certain areas/POIs considering heat load (by analysing and mapping the climate and shading data on which the model is based). If implemented consistently across multiple areas, these measures have enormous potential to protect vulnerable populations and maintain the viability of cities (Foshag et al. 2020).

3 Methods

Urban heat adaptation is a multifaceted issue that involves both individuals and communities, necessitating an understanding of a variety of structural, climatic, social, and personal factors. A multi-methodological approach is required to capture and improve the understanding of the mobility-related challenges that arise during heat events.

With our practical and evidence-based approach, we were able to identify the needs of the population in a very differentiated way and make a low-threshold contribution to local heat mitigation. The approach was developed in a pilot study (Foshag et al. 2020) and was applied and significantly further developed in the HEAL project (Heat adaptation for vulnerable population groups) at Heidelberg, Germany (https://www.geog.uni-heidelberg.de/gis/heal_en.html). The project focused on the development of a heat stress avoidant route planner for pedestrians and complementary support via maps and general information on heat protection. The routing solution is based on a general routing application without a specific focus and has been developed by the HeiGIT team in collaboration with the Geoinformatics department at Heidelberg University (Novack et al. 2018, Ludwig et al. 2021, Neis & Zipf 2008). Furthermore, we demonstrated that the inter- and transdisciplinary approach can be extended by specific methodological tools depending on the objective or need. Through the HEAL project, we have expanded our transdisciplinary toolkit, thereby increasing its applicability and transferability. This innovative, evidence-based and practice-oriented approach, supported by a range of participatory tools and in dialogue with municipal stakeholders (supporting community activities such as developing a heat action plan), represents our understanding of transdisciplinary research on climate change adaptation and bridges the gap between scientific knowledge, public needs and municipal application. In addition, the approach came close to localised risk assessment, which can be understood as the interaction of hazard, exposure and vulnerability, and took into account the impact of heat as perceived by urban dwellers (Sandholz et al. 2021).

From surveys and interviews (independent of time and space) (Castan Broto & Bulkeley 2013, Adler et al. 2018, Lawrence et al. 2022, Braun et al. 2021) to *Mobile Instant Messaging Interviews* (MIMI*s*) (less formalised, directly integrated into everyday life) (Kaufmann & Peil 2020, Kaufmann et al. 2021, Gibson 2022) and interactive city walks (from the perspective of those affected) (Sarzynski 2015, O'Neill & Roberts 2019, Scorza et al. 2021), a comprehensive and differentiated picture of the target groups and general findings on heat stress was compiled in this study (Fig. 1). In addition, the study employed interactive formats, such as interactive expert walks and workshops, to record mutual needs and possible inputs from scientific and practical partners (Fig. 1). Other social science methods, such as expert interviews, were also used to examine the administrative urban framework and the requirements for capturing the research results of the city's practical partners (Fig. 1). Simultaneously, integrating practice partners and collaborating closely with local practice experts provides access to city-specific data, such as the 3D city model, which serves as the database for heat stress modelling. Finally, the recorded results were implemented in the database. The modelling is based on a cost-benefit function that considers multi-criteria data input. The prescriptive surveys' results serve as input factors for the heat stress model, which forms the basis for routing. Prioritization and weighting were proposed based on the participatory surveys and developed step by step as part of the technical implementation. The responsibility for technical integration and implementation rested with the geoinformatics and modelling experts in the project team. They collaborated with practical partners, such as the city's digital agency, to address technical challenges, e.g. including real-time data interfaces.

The aim of applying the set of methods was to identify the specific needs of vulnerable groups and the general population in terms of heat avoidance routing. General challenges in everyday life during heat events play a role as well as practical conditions that limit mobility. For the heat avoiding routing as a low-threshold tool to support healthy mobility during hot days, these inputs from the population are crucial and cannot be fully captured by a broad-based survey. Other (scientific), non-participatory methods were used to identify additional local conditions that influence the development of heat avoiding routing (e.g., microclimatic conditions in the urban area). Figure 1 provides a comprehensive overview of the different methodological approaches that led to the comprehensive picture of routing requirements.

In line with the transdisciplinary approach, adaptation measures including the routing tool have been developed on the basis of the results, as a response to heat stress developed in co-design with practitioners and the urban population. The results have been reflected back into practice several times during the ongoing process to support iterative and reflexive activities and create positive side effects.

The consideration of different target groups in the approaches was also explicitly addressed. For example, some sub-studies addressed specific target groups (e.g., pregnant women) with specific tools, have been tested and evaluated with the help of differently composed groups (e.g., people with mental illnesses vs. older people) or addressed to the public (e.g., survey addressing the public in summer 2022) (see Tab. A1 appendix).

3.1 Heat-avoidant routing application to support urban heat adaptation

As climatic conditions change, urban mobility habits are also affected. Activities may be delayed or avoided, leading to neglected or postponed appointments, and in some cases, loneliness for older people who isolate in their homes. Heat-avoiding routing can help counteract these behavioural changes. Shady, refreshing pathways facilitate movement and

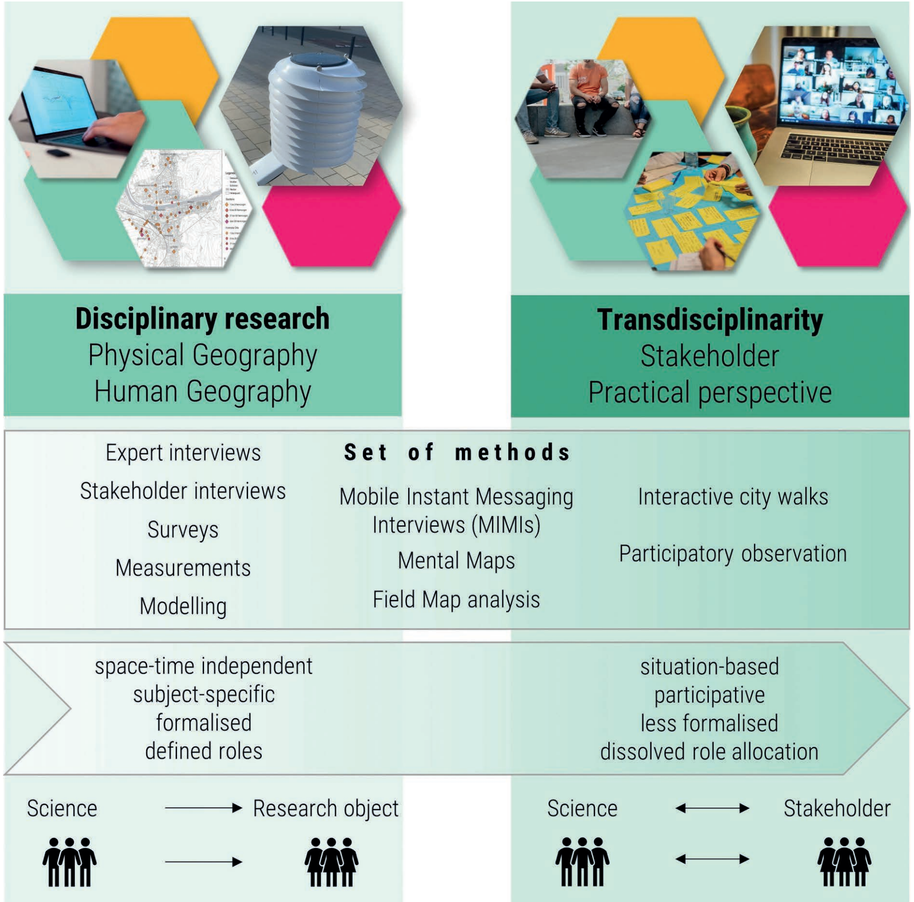

Fig. 1: Inter- and transdisciplinary design integrating quantitative and qualitative methods. The different tools complement each other as they follow different approaches and are characterised by different dimensions. Thus, we progressively delve into the perspectives of vulnerable population groups and city administration experts to develop a heat-avoiding routing approach and assess the tool's suitability.

daily routines even during warm weather. Route recommendations highlight areas with high heat levels, as well as areas that are cooler, increasing awareness and knowledge of the locale (Pioppi et al. 2022, Becker et al. 2023).

The study focuses on participative developing of a heat-avoiding routing tool. The routing is founded on free geodata from OpenStreetMap, as well as municipal geodata like a 3D city model that models shadow projection throughout the day, microclimate, and local weather data (Novack et al. 2018, Ludwig et al. 2008). The user interface has been adapted for the general public, with a special focus on vulnerable groups. After selecting the starting and destination points of a pre-planned route, the user interface suggests routes with low heat loads. These displayed routes are segmented by colour to indicate heat loads, which can be low, moderate, or high. Additionally, the user can select the desired walking time for the route. The model processes the spatial and temporal input and presents heat loads of various alternative routes.

The methods used in this study to determine routing requirements and appropriate frameworks to render the tool functional and relevant are detailed below.

3.2 Surveys

Surveys were conducted to gain a deeper understanding of perceived heat stress in Heidelberg. Of particular interest were the location of hot spots, the support people need to protect themselves from the heat, and the valuation of a heat-avoidance route service.

Most of the surveys were conducted digitally using the online questionnaire tool "SoSci Survey" (https://www.soscisurvey.de/). Some smaller surveys were also conducted face-to-face or focused on sub-target groups (e.g., pedestrians). The study participation call was disseminated through diverse public and private channels including social media, mailing lists, and displays. The city partners and their network provided support and access to appropriate institutions such as senior citizens' facilities.

The questionnaire format extended beyond binary options. There have been various question formats included: open questions, rating questions, closed questions with multiple answers, single choice questions etc.

A total of 836 participants took part in the various surveys. Of these, 629 valid cases were included in the large online survey in summer 2022. Cases that were incomplete or were terminated early have been removed from the raw dataset. The results were analysed using MS Excel and IBM SPSS Statistics and presented in graphs and tables. The standardised questioning of knowledge and opinions allowed a quantitative statement on certain behaviours and perspectives (Braun et al. 2021, Vogt & Abood 2020, Lieberknecht et al. 2023, Capstick et al. 2015, Lee et al. 2020, Wagner et al. 2019, Benevolenza & DeRigne 2019, Wolf et al. 2010, Rattray & Jones 2007). Although the number of cases is high (n=629), the analysis of participants does not fully meet the criteria of representativeness (in terms of the distribution of characteristics such as age, gender etc.) (see Fig. A1 appendix) (Duffy et al. 2005, Braun et al. 2021, Rattray & Jones 2007). Common standards for questionnaire development and survey methodology were used to develop and implement the questionnaires (Rattray & Jones 2007, Braun et al. 2021)

3.3 Interviews

Interviews with vulnerable people and experts from different domains were used to identify explicit challenges of heat protection at a personal level for vulnerable people and to define practical and functional frameworks for adaptation and the heat avoidance routing tool.

A total of 35 interviews were conducted with experts such as city administrators, senior citizens' services, the mobility sector and representatives of vulnerable groups. The interviews were conducted in person or digitally and were recorded, transcribed and analysed. Interview guidelines were developed to facilitate a consistent interview process. The guidelines have been structured according to main questions, sub-questions and optional questions and have been tailored to each interviewee (Anderson & Kirkpatrick 2016, Bittner & Stössel 2012, Kaufmann & Peil 2020, Küsters 2022). The interview's primary topics related to the challenges of coping with daily life and mobility during the heat, as well as appropriate adaptation measures at individual and community level, depending on the focus of the interview and the respondent.

With a few exceptions, for which explicit consent has been obtained and documented, the results are presented anonymously. The selection of the experts was carried out by means of a broad enquiry in which suitable actors were contacted by telephone, e-mail or through personal networks.

In order to understand the individual perceptions and heat adaptation strategies of vulnerable groups, we tested *Mobile Instant Messaging Interviews* (MIMIs) (Kaufmann & Peil 2020, Kaufmann et al. 2021, Gibson 2022) (n=8). Theses interviews were performed using a small sample (n=8) of pregnant women as a test case. MIMIs refer to a digital interview format that can be conducted over a day or longer via a messenger service, aiming to accompany interviewees in their daily lives and engage in targeted, repeated interaction (Kaufmann & Peil 2020, Kaufmann et al. 2021). Although problem-focused face to face interviews allowed for trust to be built, direct conversation and sharing of past experiences, ideas, criticisms and desires are subject to the effects of social desirability and recall bias in responses. The MIMIs (Kaufmann & Peil 2020, Kaufmann et al. 2021) helped to provide more detailed information on individuals' everyday behaviour and perception of heat. MIMIs (as well as face to face interviews) allowed for direct interaction between respondent and interviewer as well as spontaneous further questions or clarifications of certain statements during the event, which increases the accuracy of the data (Kaufmann et al. 2021). MIMIs also allowed for a variety of data to be collected, as most messenger services allow participants to use emoticons, gifs, videos, photos or voice messages to answer questions, without the collection method being intrusive, as the use of messenger services is part of many people's everyday lives (Kaufmann & Peil 2020, Kaufmann et al. 2021, Gibson 2022). MIMIs served as a method that allows the interviewee to enter their daily life without interrupting their current activities ensured an undistorted picture of the participant's life situation (Kaufmann & Peil 2020, Kaufmann et al. 2021).

The evaluation for both interview types was carried out using defined category systems (partly with the help of the software MAXQDA) and varied slightly between the different interview variants or target groups. The evaluation process is based on qualitative content analysis according to Mayring (Mayring 2021, Mayring & Fenzl 2019, Weber & Wernitz 2021). The transcription of the interviews followed the rules of Kuckartz (Kuckartz 2014, Kuckartz 2019).

The method allowed for more qualitative evaluation of different perspectives on a given topic. Individual assumptions have been compared qualitatively but not quantitatively, as the opinions do not have to be representative (Gläser & Laudel 2009, Kaufmann et al. 2021, Vogt & Abood 2020, Kuckartz 2014, Schmidt et al. 2019).

3.4 Interactive city walks including ethnographic methods

The interactive city walks were adjusted as a method to address heat adaptation measures and challenges directly in the city. Several methods, some of them ethnographic, were integrated into the walks in order to capture a differentiated discussion from different individual and professional perspectives in a short period of time. The integrated methods comprise narrative interviews, participant observation, participatory mapping, mental maps and photovoice. Each of these methods will be discussed in more detail below.

Participatory formats can help to understand people's demands for public space and to incorporate their input into future urban adaptation projects (Hanslmaier et al. 2022, Hanslmaier et al. 2018, Cvitanovic et al. 2019, Koegst et al. 2022). The use of ethnographic methods, especially participant observation, was an appropriate way to gain an in-depth insight into the realities of people's lives (Musik 2016, Sarzynski 2015, Engels & Rogge 2018, Reinharz 2017). Other methodological components that support the purpose and focus on hot and cool places across the urban area and individual adaptation strategies were narrative interviews (Anderson & Kirkpatrick 2016), photo-voice method (Simmonds et al. 2015, Seitz & Orsini 2022, Wihofszky et al. 2020, Wang et al. 1998) and hotspot-mapping (Reinharz 2017, Sarzynski 2015, Scorza et al. 2021, Vanderlinden et al. 2020, Baumeister et al. 2020). The methods mentioned were incorporated into the city walks, and participants of the walks were actively engaged in the methods throughout the tour.

The interactive walks took place in small groups (comparable vulnerable characteristics) on different days. The weather on each day was similar to a summer day, without extreme heat stress, so as not to expose the participants to extreme stress. The routes, breaks and total duration were individually adapted to the participants needs (more frequent breaks, cooling down in air-conditioned indoor rooms, etc.). Four interactive walks were conducted in total, two with vulnerable groups and two with experts. Walk one involved two older people and their companion. Walk two included four participants with mental illness and a caregiver. Walk three had four experts participating, and walk four involved three experts in the fields of urban planning and health protection. In total, fifteen individuals participated in the walks.

Important for generating information on urban and individual heat adaptation of vulnerable groups of people was the broad understanding of mobility patterns in urban space (Fernandez-Heredia & Fernandez-Sanchez 2020, Foltýnová et al. 2020, Stinder et al. 2022). The classic method of participant observation has been implemented through city walks that follow specific routes of the daily life of the people concerned (Koegst et al. 2022, Ende 2020, O'Neill & Roberts 2019, Seckelmann & Hof 2020). After accompanying a group of people through the urban area, a narrative interview was conducted (Anderson & Kirkpatrick 2016, Küsters 2022). The narrative interview had the advantage of providing the most authentic perspective on urban and individual heat adaptation from the perspective of those at risk, thus enabling the identification of important behaviours or health challenges in everyday life related to heat (Ohlbrecht 2016, Araos et al. 2016, Kandarr et al. 2014).

The photo-voice method is a qualitative photographic tool that is used in various fields of social research and is also conducted in workshops (Seitz & Orsini 2022, Simmonds et al. 2015, Wihofszky et al. 2020). As with other methods relevant to this work, the aim of the photo-voice method was to gain knowledge about the perspectives and experiences of vulnerable people on heat-related issues, in particular individual and urban heat adaptation. In the classic application, participants are asked to take their own photographs of places, objects or situations that are particularly relevant to the issue and reflect their own perspective (Seitz & Orsini 2022, Wang et al. 1998, Wang & Redwood-Jones 2001). When utilizing the photovoice method on a regular basis, test subjects produce photographs during the survey phase in response to a specific task, which are later discussed in a workshop (Seitz & Orsini 2022, Wang et al. 1998, Wang & Redwood-Jones 2001). For the interactive city walk, we opted for a modified approach to avoid overloading the interactive city walk format. The participants brought their own photos, which were not related to the city walk. The photos should show places where there is a high level of heat stress, or situations or places that people associate with heat stress. Participants discussed the photographs and added text, drawings or captions on the paper provided, adding further thoughts to the existing perspective through the photograph (Hartung et al. 2020, Wihofszky et al. 2020, Wang et al. 1998). Alternatively, in the context of this study, photographs were prepared and introduced into the discussion by the study leader.

The mapping of both cool and heat-affected locations as well as conducive infrastructure in the urban area was carried out as hotspot mapping, which basically involves documenting and mapping occurrence and distribution of heat as perceived in the city area in as much detail as possible (Völker et al. 2013, Baumeister et al. 2020). In a quiet atmosphere, an official map of the city of Heidelberg was spread out on paper and sticky notes were used to mark places. The notes could contain information such as the name of the place, but also further details. While working on the map, the participants discussed and exchanged their individual views on the places or gave each other hints on cool places in the city.

3.5 Measurements

On-site measurements taken on hot days have provided evidence and quantification of heat stress in selected sub-spaces. This measurement has helped to underpin individuals' perceptions of heat stress.

The measurements were taken out of interest in the heat load and solar radiation during the midday hours between 11:30 and 14:30 on 18 and 19 June 2022. The two consecutive days have been classified as hot days (maximum air temperature ≥ 30 °C) without cloud cover. The air temperature in °C, the surface temperatures of facades, walls, etc. (if present) in °C, the surface temperatures of the floor covering in °C, the wind speed in m/s, the relative humidity in per cent and the time of the measurement were recorded at approximately 25 metre intervals at 90 measurement points on 'Mittermaierstraße' and its extension, 'Berliner Straße', and at 30 measurement points along the 'Bahnstadt Promenade' (see section on study site and Fig. B in the supplementary material). Following the measurements, infrared images were taken with an infrared camera.

The equipment for the in-situ measurements consisted of an infrared thermometer (pyrometer) for determining surface temperatures, a ventilated psychrometer for determining air temperature and relative humidity, a hot-wire anemometer for determining wind speed and an infrared camera for thermal imaging.

3.6 Micro-climate modelling

By modelling the current state of heat stress on hot days and simulating a heat-adapted state with appropriate measures in selected study areas, the effects of adaptation were quantified. This approach yielded a differentiated understanding of small-scale heat distribution, in addition to measured and perceived heat stress, and demonstrated the impact of specific climate adaptation measures at the pedestrian level.

The micro-climate modelling was performed using ENVI-met, a three-dimensional flow and energy balance model whose physical foundations are based on thermodynamics, atmospheric dynamics, and the laws of fluid mechanics (Salata et al. 2016, Liu et al. 2021, Huttner & Bruse 2009). It was used to simulate the interactions between surfaces, the urban environment and vegetation, and the atmosphere, taking into account urban structural characteristics such as building dimensions or vegetation characteristics (Huttner & Bruse 2009). The spatial resolution is typically between 0.5-10 m, depending on the size of the area (Salata et al. 2016). Based on the urban structures, the equations include the distribution of air temperature, humidity, different radiation fluxes and turbulence that shape the microclimate. The interaction between vegetation and the atmosphere was also calculated, resulting from, among other things, water vapour exchange, water uptake by roots and the change in leaf temperature during the day (Huttner & Bruse 2009, Tsoka et al. 2018). The spatial and temporal resolution allowed the analysis of small-scale interactions between plants, buildings and surfaces in terms of microclimatic characteristics (Tsoka et al. 2018, Salata et al. 2016, Loibl et al. 2021). Similarly, thermal indices have been used to make statements about thermal comfort for the human body (Salata et al. 2016, Nastos & Matzarakis 2008).

ENVI-met, with its microclimate simulation capability, is used, for example, in urban design to identify differences in implementation scenarios during a planning phase and to select the best design in terms of expected microclimatic changes (Huttner & Bruse 2009, Liu et al. 2021). The accuracy of the input data affects the extent to which the reality of climatic conditions can be represented (Liu et al. 2021). The input data used by ENVI-met in the most accurate resolution possible are the geographical location and size of the study area (see section on study site), the structural characteristics of the urban surface: building dimensions, roads/pedestrian and cycle paths, soil, surface and vegetation characteristics, the meteorological data of the simulation day, cloud cover, initial temperature and humidity, and wind conditions (Liu et al. 2021, Huttner & Bruse 2009, Lee et al. 2019, Goldberg et al. 2016).

The data basis for the urban structure in this study was a 3D city model provided by the City of Heidelberg (FME Workbench 2022.1.1). The building heights for the model base were derived from this using a measuring tool in CAD. The horizontal building dimensions were also taken from the 3D city model and additionally from the real estate cadastre of the City of Heidelberg, which can be accessed via the geoinformation system of the City of Heidelberg (GTIS). Surface and vegetation characteristics were taken from the aerial map also made available there.

ENVI-met provides a database of surface properties relevant to thermal effects, such as albedo (Huttner & Bruse 2009). The meteorological data came from the nearest weather station. In this case, data from the 'Stadtbücherei' (library) station in the Heidelberg district of 'Bergheim', near 'Mittermaierstraße', was used. The station is located on the gravel roof of the building (118 m above sea level; 6 m above ground). Precipitation, air temperature, humidity, wind speed and wind direction are recorded every 10 minutes. To calculate thermal indices such as UTCI and PET, several approximations of human biometeorological parameters are assumed (Loibl et al. 2021, Nastos & Matzarakis 2008). These correspond to a middle-aged male of average height, walking.

A square section was chosen to cover the largest possible area based on the model (Huttner & Bruse 2009, Chatzinikolaou et al. 2018). In this study, a 225x225x30 grid with a resolution of 2 m has been used. The presentation of the results included the 200x200x30 grid, corresponding to 400x400 m. The additional 25 grids in the outer area were used to improve the result, as effects in the edge area can distort the result. Accordingly, the two selected study areas were placed in the centre of areas (Loibl et al. 2021, Salata et al. 2016).

The current state of the study areas was modelled and then a target state scenario was developed and modelled based on established climate change and heat adaptation measures. The adapted scenario should improve heat exposure through shading (natural and artificial), changing the surface characteristics of surrounding buildings (changing albedo, implementing facade greening), reducing additional heat input from motorised traffic by changing traffic routing (reducing lanes) and improving the overall (thermal) quality of stay (see Tab. 1). Co-benefits of these adaptation measures would be a better spatial distribution of cyclists and pedestrians and traffic areas, improved air quality and reduced noise pollution.

Tab. 1: Summary of individual adaptation measures and behavioural adjustments during heatwaves. The general population, as well as individuals in vulnerable groups, employ a range of measures (both conscious and unconscious), to prevent heat-related illnesses. Sometimes, these measures are accompanied by alterations to their daily routines.

Individual adaptation measure	Examples
Use of urban infrastructure in public space	• Avoiding direct sun exposure and seeking shaded areas • Seeking out air-conditioned rooms • Use of seating to take breaks • Avoiding heavily sealed areas • Seeking out blue infrastructure in urban areas (outdoor swimming pools, natural water areas)
Mobility, physical activity and public transport	• Use of public transport • Shifting physical activities to morning and evening hours • Staying indoors / in the flat during the day • Preference for shady, green paths
Information procurement	• Use of information services • Get informed by public information via city's website or social media
Adaptation of everyday life and social life	• Sufficient / adapted fluid intake • Sun protection (appropriate clothing, headgear, sunscreen) • Change of diet to easily digestible food • Postponing / cancelling appointments / commitments • Interaction with friends / family
Individual adaptation measures at home	• Morning and evening ventilation • Darkening during the day • Use of fans / air conditioners • Cooling measures (damp cloths, showers, Kneipp treatments)

3.7 Study area

Heidelberg is located in the Upper Rhine Rift Valley in south-western Germany (49°25´N / 8°43´E at 114 m a.s.l.). The city, with a population of approximately 160,000 (Stadt Heidelberg 2020) is located on the eastern shoulder of the rift valley and at the transition to the antecedent Neckar river valley. In general, climate change is increasingly leading to a 'Mediterraneanisation' of the climate in the area with rising average summer temperatures (more frequent and intense heat waves) and more frequent heavy precipitation in the winter months (Stadt Heidelberg 2015, GEO-NET Umweltconsulting GmbH & ÖKOPLANA 2017, Foshag et al. 2020). Since 1990, the area has experienced 17 intense heat waves lasting at least 14 days with an average daily maximum air temperature of at least 30 °C (Deutscher Wetterdienst 2022, Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg 2015, GEO-NET Umweltconsulting GmbH & ÖKOPLANA 2017). In particular, the densely built-up inner-city areas (e.g., the 'Bergheim' or 'Neuenheimer Feld' districts, where many critical infrastructure facilities such as the main railway station or several clinics are located) frequently experience overheating on hot days, with small-scale microclimatic variations (Foshag et al. 2020, Stadt Heidelberg 2015).

On-site measurements and micro-climate modelling using ENVI-met focussed on two areas: 'Mittermaierstraße' (central district 'Bergheim') and 'Promenade' (district 'Bahnstadt'). Both are highly frequented areas. 'Mittermaierstraße' is a four-lane road with pedestrian and cycle paths on both sides. The Promenade is a shared pedestrian and cycle path that connects the 'Bahnstadt' district with the western and central parts of the city.

An overview map of Heidelberg with two detailed sections of the study areas 'Mittermaierstraße' and 'Promenade' shows the spatial situation (Fig. 2).

4 Results

Our chosen inter- and transdisciplinary approach allowed for a gradual deepening of key aspects to meet the challenge of reducing heat stress in everyday life, zooming in on individual aspects of urban heat stress and highlighting co-designed adap-

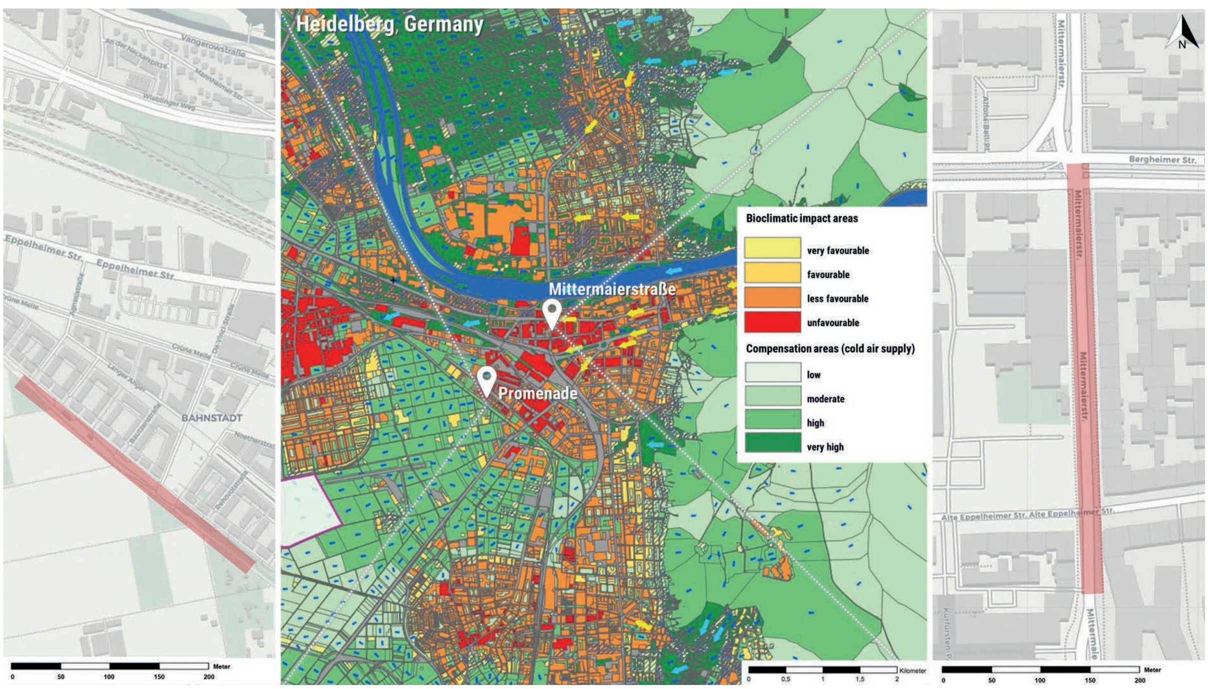

Fig. 2: Map of the city of Heidelberg including detailed map of the two focus areas. The central overview map incorporates the climate analysis map from the City of Heidelberg's Urban Climate Report (2015). Areas coloured red represent areas with unfavourable bioclimatic conditions, areas coloured green are compensation areas that supply the urban area with fresh air. The two detail sections on the left (Promenade in the Bahnstadt district) and on the right (Mittermaierstrasse in the Bergheim district) show the location of the two study sites where microclimatic measurements, infrared images and modelling of the actual and an adapted planned state have been modelled. The detailed maps do not include climate information.

tation measures. Depending on the methodological implementation and focus during the workflow, differentiated scientific impulses and practical results were considered and combined in an impactful way (Fig. 3). Taken together, the results of the co-design process provided appropriate thermal adaptation strategies that meet the needs of vulnerable people and are directly incorporated into the development of the routing approach. The main objective was to identify the needs, requirements and local conditions that influence the development of the heat-sensitive routing service as a concrete support measure to ensure mobility on hot days. A meaningful and practical design of the routing tool cannot be guaranteed without integrating the results of the interactions with the subsequent user groups of the routing application as well as the supplementary methodological explorations, such as microclimatic measurements. The developed and applied transdisciplinary workflow also represents a methodological outcome that enables the generation of content knowledge on transdisciplinary research.

Figure 3 provides an overview of the relevant key findings that influenced the development of the routing tool and supporting information materials.

It is important to consider that the heat-preventing routing tool is inclusive. This ensures that the needs of vulnerable individuals regarding distances and heat stress are considered, while also being practical and usable for non-vulnerable individuals who wish to reach their destination quickly and without experiencing heat stress. Specifically, this requirement refers to the maximum detour length, which may need to be integrated to avoid heat stress compared to the shortest route. Diversions must not be too long or too far for several reasons, including

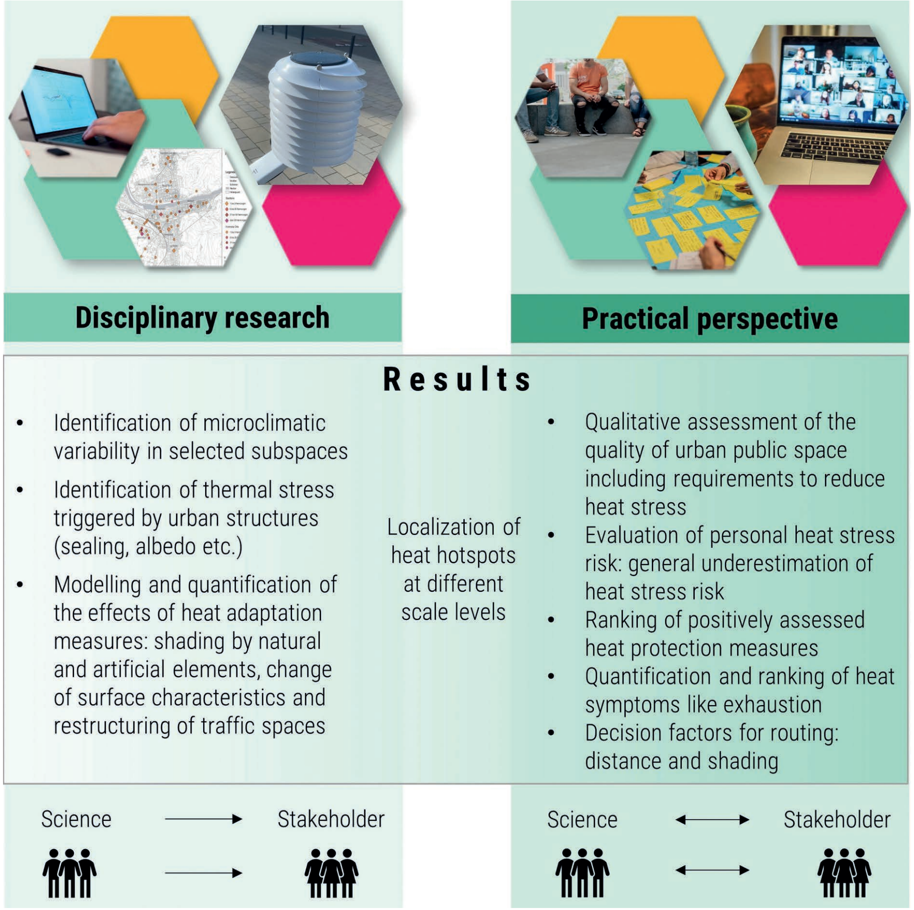

Fig. 3: Overview of the general results of the inter- and transdisciplinary approach, integrating both quantitative and qualitative methods. Depending on the focus and the tools used, differentiated scientific and practical results can be generated. Taken together, they provide an in-depth insight into the heat stress exposure at the study site and the detailed challenges and needs of the (vulnerable) population. The data and analysis help to develop appropriate heat adaptation strategies in a co-design process that meet the needs of vulnerable people.

efficiency (non-vulnerable) or distance limitations caused by disability (vulnerable individuals).

In addition, the data has been gathered in anticipation of a differentiation of the routing tool in later development stages. This will become even more important if different user profiles are integrated into routing.

At the meta level, the results indicate general insights into heat stress and heat protection in Heidelberg. These findings can assist the city administration and critical infrastructure in prevention and adaptation efforts. Additionally, they provide valuable information for accompanying materials such as brochures, instructions, analogue maps, and presentations that follow the publication of the routing tool. The completion of this project will be announced through public workshops and practical excursions planned for summer and autumn 2024.

To inform and raise awareness without overwhelming or scaring the user, it is important to adopt a sensitive approach and design accompanying materials that are adapted to different user groups. For example, section 3.4 discusses the importance of self-assessment or lack of awareness of one's own vulnerability or heat stress risk in this context.

In the results section, individual results of the multi-method approach are presented separately and grouped according to methodological perspective, followed by a summary of the conclusions for the development of heat stress avoidant routing (see 4.5).

4.1 Measurements and urban microclimate modelling using ENVI-met

The results of measurements and ENVI-met modelling (status quo) on highly frequented and heat exposed routes showed the increased thermal stress in the urban area of Heidelberg. Figure 4 shows the differences between the current state and the adapted state for different bioclimatic parameters and thus the effect of the proposed adaptation measures. The air temperature at 14:00 is largely reduced as a result of the planned measures. In the area of shading by awnings and the greening of the facade, a reduction in air temperature of -0.2 K can be observed as a result of the measures, and there are also slight positive effects of -0.1 K along the avenue of trees, which serves as a separation between the pedestrian/cycle path and the car lanes. Marginal increases in air temperature occur only at very small scales. For the average radiant temperature, the green strip leads to a reduction of almost -2 K. Reductions of up to -9 K can be seen through the trees. Sun sails reduce the average radiation temperature by up to -16 K by shading, but at the same time increase the average radiation temperature by up to 3 K in areas where they return the reflected radiation. It follows that the air temperature is only affected by the measures to an extent of measurement uncertainty, while the radiant heat is effectively reduced. The specific humidity is also slightly increased up to a height of 1.4 m due to the greening measures. The effect on wind speed is negligible in this case, but can be significant.

According to the overall modelling results of potential heat adaptation scenarios, urban greening as well as artificial shading by temporary awnings can counteract heat stress (Fig. 4). Following the results, trees can reduce the UTCI (Universal Thermal Climate Index; combined thermal index) (Nastos & Matzarakis 2008, Ketterer & Matzarakis 2014, Salata et al. 2016) in the study areas by -4 K, and awnings by up to -4.5 K.

The need for urban adaptation measures was also highlighted by some thermal images of selected routes. For example, on a hot day in June 2022, surface temperatures of up to 59 °C were measured in the 'Bahnstadt' district (Fig. 5). The 'Promenade' is a heavily used pedestrian and cycle path that connects the 'Bahnstadt' district with the old town and areas on the outskirts of the city. Many families live in 'Bahnstadt' and there are several children's playgrounds along the 'Promenade'. As the image on the right shows, these areas were uncomfortable to use in hot weather as they provide little shade (Fig. 5). In addition, changes to the surface albedo of roofs and surface unsealing were identified as useful complementary measures. This would be reflected in the land surface temperature (LST), caused by solar radiation. This in turn is an indicator of the heating of different surfaces and affects the ambient temperature.

The relatively new landscaping does not yet provide shade for the road; artificial shade will only be provided in the area of several adjacent playgrounds. Although the significance of the thermal images is limited, in addition to the other results and surveys, they show that pedestrians and cyclists are in a stressful thermal situation on hot days. Heat avoidance routing can avoid this area and prefer parallel routes between buildings to avoid heat stress.

The results obtained from the on-site measurements indicate a temporary increase in urban temperatures, consistent with individual heat assessments obtained through other methods and reflected in the modelling findings. Moreover, the measurements highlight the significance of the dynamic routing component. Point measurements along main traffic routes show the daily temperature cycle and small-scale differences in the microclimate caused by changing shade or ventilation throughout the day. For example, temperature differences of up to 5 K (fluctuating around the daily maximum around midday) occurred along the study areas (distance approx. 1 km at 'Mittermaierstraße') within two hours on a hot day (see Fig. A2 appendix). This highlighted the importance of a dynamic routing approach that takes changing weather conditions into account when creating routes and meets the needs of vulnerable people, who are more likely to spontaneously adapt their errands to weather conditions due to retirement or illness than people who are healthy and involved in the daily work routine (Neis & Zipf 2008, Ludwig et al. 2021, Novack et al. 2018, Tost et al. 2019).

The modelling, thermal imaging, and measurements indicated that gradual adaptation to heat stress through measures such as unsealing, shading,

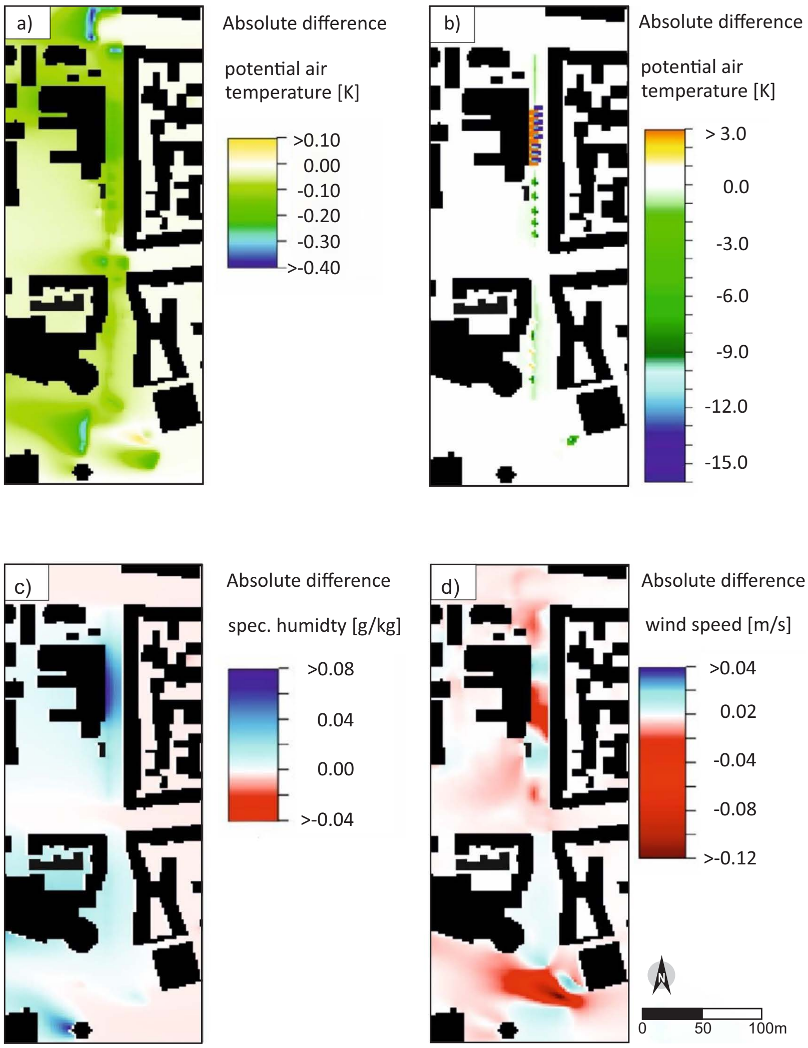

Fig. 4: Presentation of the effects of the adaptation measures in the study area 'Mittermaierstraße' on the most important parameters for the human bioclimate. Shown are the differences in absolute potential air temperature (a) in K, mean radiation temperature in K (b), specific humidity in g/kg (c) and wind speed in m/s (d) at a height of 1.4 m above ground level, corresponding to the height of pedestrians and cyclists at 2 p.m., for the scenario with climate change adaptation measures and lane reduction. They show the effect of the measures taken, where in a) and b) the reduction leads to an improvement in thermal adaptation, while in d) a reduction is seen as more negative for ventilation and thus for thermal adaptation. In c) the effect depends on the other parameters and can be both positive and negative. Location of the study site is shown in Fig. 2.

Fig. 5: Infrared image of the surface radiation temperature (LST) on a hot day in July 2022 on the 'Promenade' in Heidelberg's 'Bahnstadt' district. The area of the infrared image is indicated by the red rectangle. The path is paved with concrete and runs along a lawn and, on the other side, directly along the housing estate, separated by a wall of stamped concrete. The surface temperature visualisation also shows natural shading from trees, although this is minimal as the vegetation is relatively undeveloped due to new planting. There are a few benches, most of which are not shaded. The surface temperature has no direct effect on the air temperature as some of the energy is absorbed and later released through radiation. However, surface radiation also increases heat stress. The image therefore shows the significant overheating of the area at midday (indicated by the colour scale in degrees Celsius).

and greening can significantly increase the potential for heat avoidance routing based on these factors.

4.2 Perceived heat hotspots in Heidelberg, Germany

Trough surveys, expert interviews and interactive city walks (including hot spot mapping tools), we identified several perceived heat hotspots in the urban area of Heidelberg. The results related to different spatial scales: squares, streets, and larger areas such as entire neighbourhoods. The heat hotspots included the 'Bergheim' district, including the centrally located squares like 'Bismarckplatz', the 'Bahnstadt' district, with particular emphasis on two public squares, the old town (district 'Altstadt') including the main road 'Hauptstraße', the university campus 'Im Neuenheimer Feld' and the Neckar bank in 'Neuenheim' (Fig. 6). The latter is a highly exposed green space, but the natural shade provided by mature trees has been greatly reduced in recent years. The districts mentioned are characterised by dense structures, a high degree of sealing and a low proportion of green spaces. In addition, a number of other non-specific locations were identified as being particularly exposed to heat, such as the city centre in general, as well as many of the public squares (Fig. 2). The highlighted sites represent areas of particular bioclimatic stress, based on both quantitative survey methods and qualitative perceptions (see Fig. 2).

In addition to the more negative perceived heat hotspots, it was also possible to identify 'cool' places where the quality of the stay during the summer months was rated positively. These are usually characterised by a lower degree of sealing, more vegetation and trees, and thus sufficient shade. The identification of perceived heat hotspots is an example of how impulses for the generation of the routing approach were derived from the results of the interaction with the target groups. Heat-avoidance routing can avoid these heat hotspots by favouring low heat areas. The location of heat hotspots also indicated potential locations for heat adaptation measures.

4.3 Heat perception, vulnerability and adaptation measures

In general, around two-thirds of respondents to our 2022 online survey stated they found the summer heat a burden and that it affected their daily lives. High temperatures, intense sunlight, high humidity and low night-time cooling were perceived as particularly unpleasant. The most common health impairments were profuse sweating, exhaustion and fatigue, lack of concentration and headaches. Despite this, only a third of respondents said they consider their personal risk of heat stress to be high or very high. It is evident that vulnerable groups have a significantly higher risk self-assessment compared to non-vulnerable individuals. Specifically, the chronically ill category exhibits a notably higher risk of both very high and high assessment. The group of older people also has elevated values in assessing very high or high risk. For families with young children, the assessment of very high risk is marginally more pronounced. Overall the risk assessment is elevated for vulnerable individuals, although roughly a fifth (19.8 %) of those who classify themselves as vulnerable also indicate a low or non-existent risk of heat stress. Not all people at risk perceived heat as equally threatening, which may in turn lead to the trivialisation of heat-related health problems. Exceptions to the perception of vulnerability were parents with young children or babies, who perceived their children to be highly sensitive to heat, or people providing care, such as carers in retirement homes.

As pregnant women constitute a distinct subset of the vulnerable population owing to their youth and overall good health, we evaluated this group using the MIMI method and accompanying standardised interviews to assess temporary vulnerability and perceptions of exposure.

All pregnant women considered heat to be a risk. However, participants tended to focus on abstract risks not related to their personal lives or to describe dramatic scenarios in the distant future. When considering their own vulnerability to heat, participants agreed that their pregnancy contributed to their personal vulnerability but did not place them in the most vulnerable group to heat exposure ("[I feel more at risk] as if I wasn't pregnant (…), [I think my body] still has relatively good adaptation mechanisms"). Headaches, increased sweating and thirst, water retention, fatigue and exhaustion were among the most common reported heat-related symptoms. The severity of heat stress and related symptoms ranged from barely noticing the heat to heat-related absenteeism. There were also reports of mental health issues due to the heat and the associated limitations in daily life ("It affects the psyche (…) you don't want any contact with other people (…) just want to be left alone"). Additionally, the psychological stress of possible heat-related illness motivated participants to take adaptation measures. Avoiding, postponing or cancelling outdoor activities were the most commonly reported strategies. Participants re-

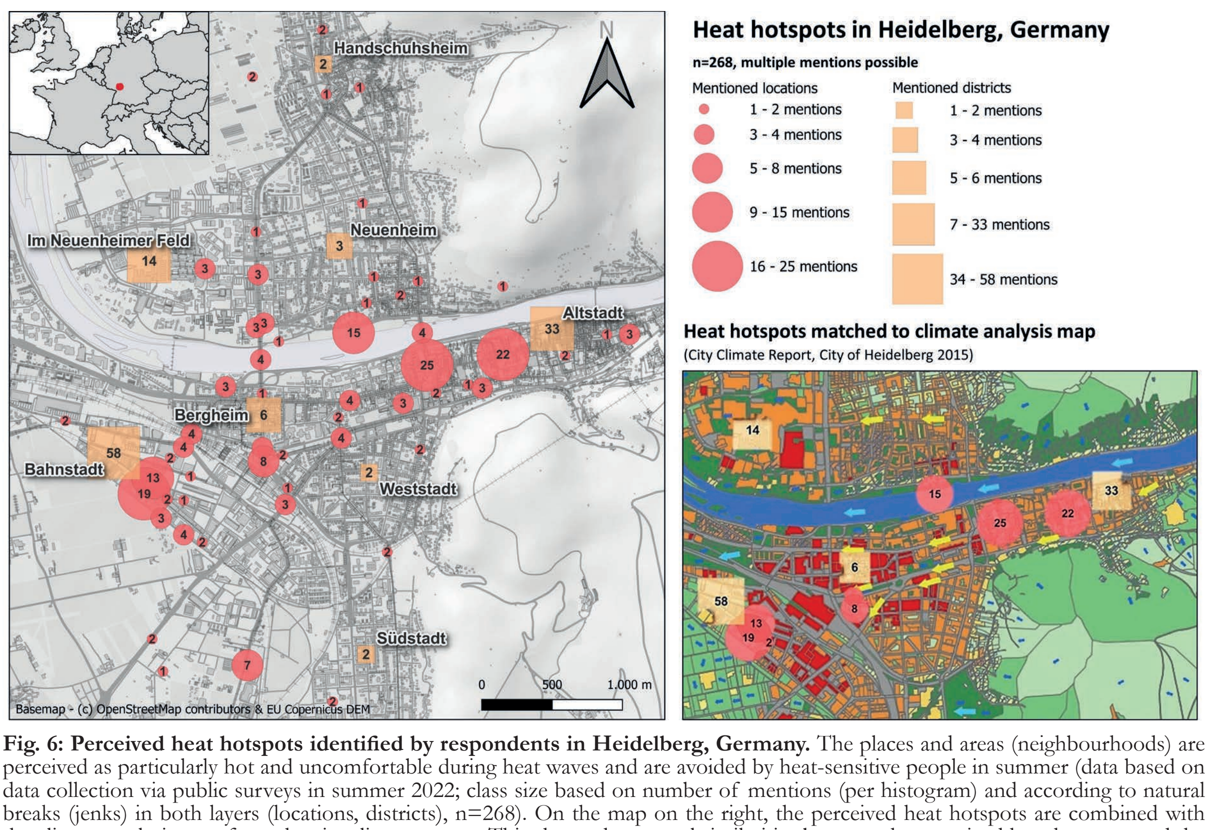

Fig. 6: Perceived heat hotspots identified by respondents in Heidelberg, Germany. The places and areas (neighbourhoods) are perceived as particularly hot and uncomfortable during heat waves and are avoided by heat-sensitive people in summer (data based on data collection via public surveys in summer 2022; class size based on number of mentions (per histogram) and according to natural breaks (jenks) in both layers (locations, districts), n=268). On the map on the right, the perceived heat hotspots are combined with the climate analysis map from the city climate report. This shows the general similarities between the perceived heat hotspots and the bioclimatically unfavourable sub-areas identified by modelling (see Fig. 2).

peatedly emphasised that maternity leave, sick leave or a ban on working due to their pregnancy allowed them to use many individual strategies that would not have been possible during their normal working hours ("I am on a sick leave to rest and I think my exhaustion is related to the heat").

Individual adaptation strategies to summer heat derived from interactions with vulnerable people were divided into five categories: *Use of urban infrastructure in public spaces* (e.g., seeking shaded areas); *Mobility* (e.g., shifting physical activity to the morning and evening hours); *Information seeking* (using information and warning services); *Adaptation of daily and social life* (e.g., dietary changes); and *Individual home adaptation measures* (e.g., darkening the home) (Tab. 1). According to the participants, the most effective behavioural adaptation to avoid heat stress outdoors was to stay in the shade. This also went hand in hand with the desire for more green spaces for shading and cooling in urban areas. Respondents also indicated that they would like to see more public water dispensers or free drinking water.

Older people also wanted infrastructures that help them to manage their daily lives regardless of the heat they experience. There was a general demand for seating in residential areas and near shopping and medical centres.

These self-assessments provided crucial information on how to communicate and design prevention and support measures for heat stress (routing tool and analogue material and maps). It is important to ensure that the information is relevant, useful, and practical for the intended user groups.

4.4 Input factors from target groups and local experts for routing applications

When considering the various input factors that can be included as routing weights there was a trade-off between different items, which can be weighted differently. Based on the summer 2022 survey, the following priorities have been identified: The most important factors in the stated route choices were distance (the shortest route is preferred) and shade (shaded routes are preferred). While vulnerable groups preferred shading to distance as the most important decision factor, non-vulnerable groups like healthy young people preferred shorter distances and rate shading of a route as the second most important factor. Vulnerable people also preferred side roads and were less likely to spontaneously set off (regardless of the current weather) (Fig. 7). There was also a general willingness to take a detour (regardless of the total length of the route) in order to arrive at the destination more relaxed, healthier and refreshed. Almost half of all respondents accepted a detour of 5 minutes, and around a third accepted a detour of up to 10 minutes.

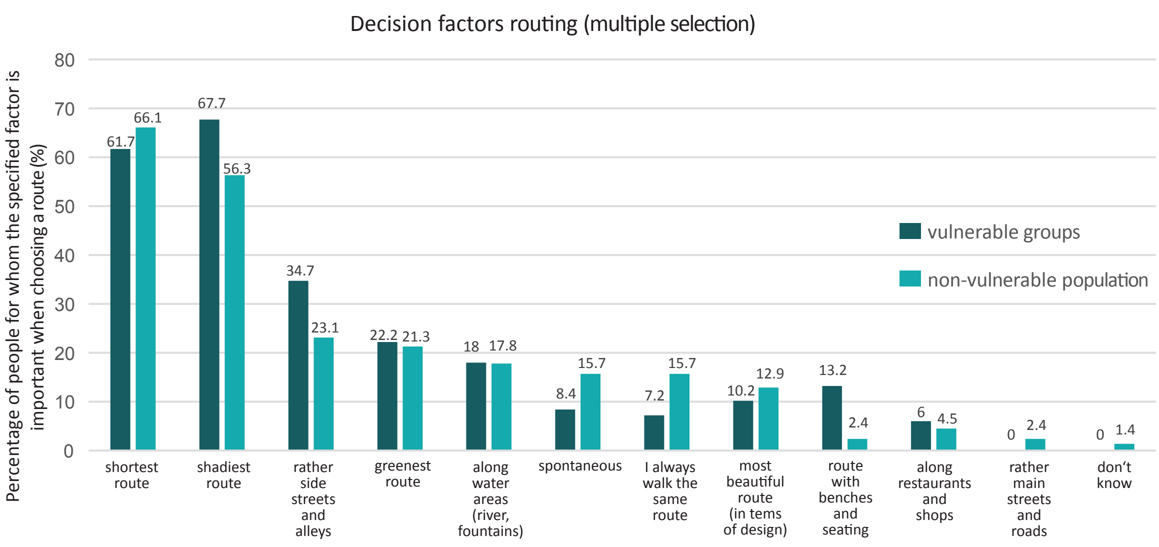

Fig. 7: Preferred criteria for route selection or detour options by respondents. The decision factors are separated according to different optimisation requirements resulting from interaction with the (vulnerable) population (n=455). These factors serve as direct input and weighting factors for routing. By applying an inter- and transdisciplinary approach, the needs of potential users are directly integrated into the development of proposed solutions, thus ensuring their practicability. For factors such as the accepted length of detours or the most important criteria for choosing a route, it is essential to directly consider user feedback and incorporate local knowledge.

The analysis revealed differences, albeit not significant ones. All findings were inputted directly into the routing application (backend modelling and frontend user interface) (Neis & Zipf 2008, Novack et al. 2018) which produces routes to prevent heat stress caused by fluctuating heat conditions. The routing development also considered the preferences and requirements of the targeted groups and the framework conditions stated by municipality experts (Tab. 2). The similarities and differences in requirements and preferences demonstrate that the tool satisfies both needs: It can be used by the general public while also meeting the efficiency and time constraints of younger, healthy individuals. Additionally, it is suitable for use by vulnerable populations as it considers important limiting factors such as time requirements, heat stress, shading, distance, and resulting detour lengths. This specialised knowledge enables the development of distinct usage profiles, such as vulnerable and non-vulnerable, as the application will undergo further development.

5 Discussion

The multi-method set and nuanced results revealed the variety of factors, data and information that must be considered when developing a heat-avoiding route service. At the same time, it is evident that even multi-criteria routing or the heat stress model, which processes and weighs data and information to generate corresponding routes, cannot consider all factors and distinguish between feasibility and relevance. In addition, some information was not available in digital form and had to be generated or approximated using our methods. For instance, data on artificial shading on paths or squares was not available digitally and had to be obtained through city walks, interviews, and surveys. However, assessing the impact of these measures proved to be challenging. We analysed the current and desired conditions of road spaces by conducting on-site measurements and modelling. The knowledge gained enabled us to create a prototype of a heat-avoiding route service that caters to the needs of vulnerable individuals while also being practical for non-vulnerable individuals who wish to protect themselves from heat stress in their daily lives.

On the other hand, we aimed to create an inclusive service that is accessible and usable for everyone. We considered the needs of vulnerable people without giving them undue weight, which could make the service unusable for non-vulnerable people. We carefully balanced the importance of the most critical factors for both vulnerable and general populations and implemented a middle ground. To ensure the tool is not only usable for heat-sensitive individuals, but also for tourists and residents, we aimed to balance the focus on impaired individuals with general usability. Therefore, the results were incorporated into interactive formats, such as city walks, and discussed with individuals and experts. In future adaptations, the information and differentiations could be used to develop different usage profiles.

In order to meet the specific needs of the target groups (vulnerable population groups) and to define their vulnerability compared to less heat-sensitive people, a comparison was made between the assessments of people belonging to a vulnerable group and the information provided by non-vulnerable people. As the routing application should facilitate the mobility of vulnerable people and ensure healthy mobility during heat events, it is important to focus on the needs of this group and differentiate them from the general public, who may not be inclined to take longer detours as opposed to those with vulnerable characteristics.

The set of methods, consisting of ENVI-met modelling, thermal mapping, in-situ measurements, surveys, interviews, interactive city walks integrating participant observation, narrative interviews and participatory mapping, as well as mobile instant messaging interviews, thus fulfilled several objectives: An exemplary and detailed mapping of heat stress in the urban area (modelling and measurements), an understanding of the perceptions, challenges and needs of the general population and particularly vulnerable groups during heat periods (surveys, interviews, partly supplemented by mental map surveys, MIMIs, interactive city walks), the localisation of heat hotspots in the urban area (participatory mapping, interviews), positively evaluated and practically implementable heat adaptation measures (surveys, interviews with vulnerable people and practical experts, interactive city walks) and, last but not least, the identification of the most vulnerable groups in the urban area and their needs (surveys, interviews, MIMIs, interactive city walks): Citizens, interactive city walks) and, as the main objective and central tool for heat adaptation, relevant and practical information for the implementation of heat avoidance routing (all methods used were included here). In this way, we were able to improve the understanding of vulnerability in the context of urban heat and with a focus on vulnerable people, and gain insights into the mindset of (vulnerable) groups when dealing

Tab. 2: Factors considered during the development of a heat-adapted routing tool. The table presents a summary of the key factors, necessary information, their integration into the routing model, and the methods or sources used to collect the data. The factors were balanced and weighted in a multi-criteria model to support mobility during heat days (e.g. heat primarily influences the European summer season, so factors like seasonality can be neglected in this case). It is important to note that routing tools may not always consider all factors, as the more criteria integrated into the model, the more complex its implementation becomes. Even multi-criteria routing has limitations, as too many criteria would result in no realistic routes being suggested. Participatory methods were used to collect, categorize, and prioritize the most important criteria. The resulting catalogue was delivered to the technical implementation team for discussion and development of the routing backend.

Factor	Routing aspects to be considered (phenomenon to be described)	Required information (relevant parameter)	Source of information and methodology used
Distance	• Average acceptable walking distances • Average acceptable walking times • Willingness to take detours • Average acceptable detour length	• Road and path grid • Road and path network distances • Accessibility of roads and paths • Incline • Traffic light system	• Open geodata via OpenStreetMap • Urban geodata available through cooperation with urban stakeholders (environmental agency, survey agency) • Interviews and surveys of the general public and vulnerable groups • Interactive expert walks
Shade	• Heat stress due to exposure to direct sunlight or lack of shading	• Building heights • Vegetation • Artificial shading measures • Position of the sun • Cloud cover • Exposure • Season • Time of the day • Perceived difference between natural and artificial shade	• Open geodata via OpenStreetMap • Urban 3D data available through collaboration with urban practice partners (building heights, tree registry, cool map with green space registry, etc.) • Solar modelling of the sun's position in temporal and spatial variability • Evaluation of weather data from temporary spot measurements and long-term monitoring by weather stations • Interviews and surveys of the population and vulnerable groups • Interactive city walks including participatory observation, photo voice and mental maps
Vegetation	• Greenness	• Mapped green spaces / green space grid • Tree register and integration into 3D terrain or city model / • Vegetation grid / NDVI dataset • Season	• Open geodata via OpenStreetMap • Urban 3D data available through collaboration with urban practice partners (building heights, tree registry, cool map with green space registry, etc.)
Weather conditions	• Heat load	• Outside air temperature • Humidity • Wind speed • Cloud cover • Clothing • Activity • Time of the day • Mode of transport	• Evaluation of weather data from temporary spot measurements and long-term monitoring by weather stations • Interviews and surveys of the population and vulnerable groups • Interactive city walks including participatory observation, photo voice and mental maps
Accessibility	• Walkability/Bikeability of routes and areas	• Incline • Restrictions/type of path (pedestrian path, cycle path, etc.) • Curb heights and widths • Condition of the surface/floor covering	• Open geodata via OpenStreetMap • Urban geodata available through cooperation with urban stakeholders (environmental agency, survey agency) • Interactive city walks including participatory observation, photo voice and mental maps • Interactive expert walks
Infrastructure	• Amenities and perception of routes and areas	• Seating options e.g. benches (especially in shaded areas) • Drinking fountains/refill stations • Public toilets • Cafes, restaurants, shops • Traffic volume • Noise pollution • Air quality • Cleanliness, neatness • Social structure (what is the social structure like in public places and which social groups are present?) • Security aspects (e.g. lighting in the dark)	• Open geodata via OpenStreetMap • Urban geodata available through cooperation with urban stakeholders (environmental agency, survey agency) • Interviews and surveys of the population and vulnerable groups • Interactive city walks including participatory observation, photo voice, MIMIs and mental maps • Interactive expert walks

with heat. These findings were fed back to the city's planning department, and their expert perspective and practical context were captured. In this way, it was possible to ensure that, on the one hand, the routing as a concrete measure would meet the needs of the users and, on the other hand, that the analyses of heat stress would be fed back to the city administration as an impulse.

5.1 Accepted detour length according to vulnerable group membership and personal heat stress risk

After considering a multitude of factors, including input from local experts and future users, it became clear that heat-avoiding routing may not always provide the shortest or fastest route between two points (it is important to note that this would not have been a novel concept, as it is already a fundamental aspect of common route services). To prevent heat stress and allow for mobility and activity along shaded paths and green and water areas, detours may be necessary. The heat stress model analyses relevant criteria in the backend, prioritises them based on the participatory results, and determines the best possible routes. These routes are more pleasant, cooler, and shaded, but may not provide a direct line / connection between two points. To limit detours and save time, we determined the average and maximum detour acceptance. The acceptance was higher for individuals who identified as vulnerable compared to non-vulnerable individuals or those who reported no risk of heat stress. However, a significant proportion of non-vulnerable individuals also accepted short detours to reduce heat stress in their daily lives.

When interpreting the accepted detours according to membership of a vulnerable group, it must be taken into account that, depending on the group, a longer detour cannot always be planned or accepted due to health conditions or time constraints in everyday life. Furthermore, a reduced willingness to take detours can be related to the perceived low level of stress. Working people usually have less time to take longer detours, as the daily routine is usually defined by fixed appointments and (working) hours. People who are on sick leave or who have already reached retirement age are generally less bound by fixed times in their daily lives and are therefore more flexible. Acceptance of a diversion of more than 10 minutes was low in all groups; the length of the path has negligible significance. In particular, people without (physical) disabilities were unlikely to accept a diversion involving such a loss of time (only 5 % of respondents without any disability). Older people showed the highest willingness to take a longer detour, about 15 % would walk more than 10 minutes longer to reach their destination relaxed and healthy. However, short detours of up to 5 or 10 minutes were (theoretically) accepted by a large proportion of non-vulnerable people (> 80 %). Behavioural adaptations in the form of detours from usual routes were generally preferred to limiting daily activities due to heat stress. Furthermore, in the context of raising awareness of heat risks, it should be noted that heat-adapted mobility (e.g., in the form of heat stress-avoiding routes with minor detours) requires certain adjustments and planning in everyday life. This acceptance should be further increased to prevent heat-related illnesses, as our results showed.

Several route suggestions are generated based on the start and destination points, current local conditions (including real-time weather data and shading during the day), and the selected time of day for the route (defaulting to the current time of day, but adjustable in the settings). These routes have a lower heat load than direct paths that ignore factors such as shading. The user is able to view the available route options and select the desired route. The routes are categorized by heat stress level (low, moderate, high) for each segment. This allows the user to identify critical areas, which may not always be avoidable due to the maximum and average accepted detour lengths, and optionally reschedule the activity for a different time of day or explore new routes. Therefore, heat-avoiding routing can be beneficial not only for vulnerable individuals but also for the general public (exploring new paths and places as an added co-benefit). Furthermore, research has demonstrated that integrating blue and green infrastructure promotes health and enhances the positive perception of areas, thereby improving overall quality of life in urban areas (Foshag et al. 2020, Lafortezza et al. 2009, Tost et al. 2019).

These findings were integrated into the feedback loops linking the local government and the scientific community, which are central to transdisciplinary settings. Interactions and surveys with the population provide impulses to the city's administration presented and discussed in meetings and workshops. This approach can facilitate the practical implementation of scientific findings, enabling local authorities to better comprehend their diverse population. In turn, utilising scientific knowledge can inform and support local initiatives, whilst involving the public can promote wider acceptance of necessary adaptation measures (Weiand et al. 2019, O'Connor et al. 2000).

5.2 Self-perceived risk of heat stress and vulnerability

Studies consistently demonstrate that the general population, as well as those classified as vulnerable, partly underestimate the health risks associated with heat (Bittner & Stössel 2012, Kandarr et al. 2014, Hatvani-Kovacs et al. 2016, Cvitanovic et al. 2019, Osberghaus & Abeling 2022). This was also evident in the results of various methodological approaches in this study. It is crucial to increase awareness of the fact that heat stress can cause or exacerbate illnesses, alter medication efficacy, and cause avoidable physical and psychological stress, particularly in densely populated urban areas, in light of current and future climatic developments. This is particularly important given the high numbers of heat-related mortality and morbidity during recent heat waves (Ebi et al. 2021, Matthews et al. 2017, Mora et al. 2017, Donato et al. 2015, Winklmayr et al. 2022). The initial step is to determine the population's self-assessment to estimate who can be reached with appropriate measures and tools. Additionally, it is important to consider how the information can be disseminated to those who may not yet have an increased risk of heat stress or do not assess it accurately. The objective is to reduce the proportion of people at risk.

In general, self-assessment of risk was significantly higher among vulnerable groups than among those classified as non-vulnerable (Reid et al. 2009, Benevolenza & DeRigne 2019). However, the perception that there is no risk was rather rare across all vulnerability characteristics in our study. People with (chronic) diseases were the most likely to perceive a very high risk. Older age (65 years and over) was the second largest risk factor, followed by very young age (infants and young children). It has also been seen that more than half of the non-vulnerable respondents considered their risk to be at least medium. In general, the result showed that non-vulnerable people also perceive heat as a health risk. The personal perception of low vulnerability compared to people of the same age was consistent with existing studies and psychological risk research (Beyerl et al. 2018, Bittner & Stössel 2012, Kurzenhäuser & Epp 2009). Reasons given include a general preference for warm temperatures or a general sense of well-being (Kurzenhäuser & Epp 2009).

Societal and social aspects may also play a role and led to misrepresentation or misjudgement (e.g., status of older people in society) (Bittner & Stössel 2012, Osberghaus & Abeling 2022, Pillich 2018). The perceived high sensitivity of young children to heat stress as observed in our study may be related to the generally much higher level of care (by parents or carers) for this group of people (Kabisch et al. 2016, Pillich 2018).

A case study from the USA (Reid et al. 2012) that took an epidemiological view of heat vulnerability included socio-economic and other health-related aspects in addition to the spatial living environment. The assessment of heat vulnerability included the spatial distribution of older people, health characteristics such as diabetes, the density of distribution of air conditioning in (public) spaces or buildings, and factors such as social isolation. The results showed a clear correlation between high heat vulnerability and the presence of these variables (Reid et al. 2012). The perceived vulnerability of an individual and the "real", possibly measurable, vulnerability therefore depended on many factors and is not only due to age, as our study also shows. Other factors influencing vulnerability to heat included personal daily routines, attitudes and sense of personal responsibility. Among other things, it is important whether people who are formally vulnerable (e.g., due to age) admit their vulnerability or consciously deal with it (Pillich 2018). This attitude may also influence the response behaviour. This is also relevant when scientists and practical partners, such as those from critical infrastructure or city administration, aim to inform citizens about the risks of heat stress and protective measures (routing tool will be presented to the public as a support tool). However, some individuals may not feel targeted by such services or information campaigns, e.g. because they underestimate the personal risk of heat stress. It is important to consider a sensitive approach, providing information at eye level and support individual experiences and learning, e.g. during interactive walks (Bittner & Stössel 2012, Reinharz 2017). The determination of self-assessments and needs will be the basis for a later reflective integration of the results while presenting the tool and additional support materials to the public.

Another study examined the relationship between heat vulnerability and income (Osberghaus & Abeling 2022). Higher financial resources can facilitate heat stress avoidance behaviour and adaptation of the living environment (e.g., purchase of shading, air conditioning, fans or staying in air-conditioned buildings such as shopping centres, etc.) and thus made a difference in perceived vulnerability or discomfort (Osberghaus & Abeling 2022). The results of a study (Sandholz et al. 2021) conducted in Bonn, Germany also showed that all socio-economic groups are exposed to urban heat stress, but to different degrees and for different reasons. Exposure was lowest among groups typically considered to be at higher risk, such as older people (Sandholz et al. 2021). Students and other younger respondents were comparatively more exposed (Sandholz et al. 2021). This suggested that urban dwellers beyond the 'classic vulnerable groups' are affected by heat stress in ways that have received less attention in current urban policies (Sandholz et al. 2021). A study (Klauber & Koch 2021) of vulnerability based on hospitalisation rates showed that men over 65 are at particularly high risk of serious heat-related illness. Overall, 25 % of the population over 65 can be considered to be at significantly higher risk of being hospitalised due to heat (Klauber & Koch 2021). This again highlights the importance of active heat adaptation and heat protection (e.g., by providing heat stress-avoidant routing), as many older participants in our study also underestimate the risk of heat stress.

5.3 Merging the results for the technical implementation of the routing application

To technically implement the heat stress model and the heat stress avoiding routing solution, we developed a catalogue of requirements that lists and prioritises relevant criteria based on the presented findings. Through iterative discussions and development steps, we categorised the criteria based on the expected benefits. The prototype considers shadow data as a crucial factor in route selection, ranking first in importance for vulnerable people and second for non-vulnerable people. It also differentiates heat stress levels per route segment based on shade and weather data, categorising them as low, moderate, or high. The basemaps provided offer different levels of additional information. For example, selecting the OpenStreetMap base layer makes infrastructural facilities, such as shops or restaurants, visible. Users can also choose to display surface conditions, such as floor covering, and path types, such as road or footpath. The tool is currently being further optimized during the finalization process. Users can personalise their experience and customise routes based on individual requirements by selecting from various options in the routing menu.

5.4 Critical reflection on integrated tools

We defined the following aspects as indicators of the success of the transdisciplinary approach: The incorporation of impulses from transdisciplinary research into administrative practice (we assume a staggered integration), the integration and visualisation of all relevant perspectives within the research process, the realisation of appropriate measures and solutions in the implementation of adaptation concepts (possibly undefined time frame), a positive response to the participation of relevant stakeholders, the establishment of a network of academic and non-academic partners for sustainable cooperation, as well as co-benefits of the developed measures (Bergmann et al. 2021, Foshag et al. 2022).

5.4.1 Surveys

The respondents to the survey in the summer of 2022 were rather young and did not represent vulnerable groups. The survey aimed to provide a general picture using the established and standardised method. The differentiated needs of the target groups were covered and complemented by other tools and methods.

The uneven gender distribution of participants could be explained by the generally higher willingness of women to participate in surveys (Menold & Züll 2010). Laguilles et al. (2011) and Smith (2008) found a similar increase in women's willingness to participate compared to men. The advantag of the online survey is that it is independent, e.g., without assistance, without the associated respondent bias and without additional effort (in terms of time, etc.) compared to an interview (Duffy et al. 2005). Anonymity is guaranteed by the procedure, which can be an advantage when answering the questions (unbiased answers, "social desirability"). Another advantage of the online survey was that it can be carried out on the move and at any time, which has a positive effect on the willingness to participate (Duffy et al. 2005). Disadvantages of the online survey, however, were that ambiguities might have remained or the questionnaire might not have been completed in full. Another disadvantage of the online survey was its reach, as the target group (e.g., the over-65s) might not be equipped with digital devices and can't be reached via online tools. To the extent that respondents who belong to a vulnerable group receive assistance in answering the questions, it cannot be assumed that their opinions was completely uninfluenced. We assume that this effect is negligible, as only about a quarter of the respondents in the online survey belonged to vulnerable groups, and these were specifically included through other tools.

5.4.2 MIMIs and interviews

Interviews are a way of capturing the perspective of individuals, such as experts or stakeholders. Interviews can also be used to generate sample statements that support or refute qualitative findings (Anderson & Kirkpatrick 2016, Bittner & Stössel 2012, Gläser & Laudel 2009). Due to the individual and personal reproduction of opinions and knowledge, the statements were usually to be interpreted as 'true'. However, they were also subject to limitations regarding factors such as 'social desirability', which cannot be clearly identified from the data. In order to obtain further results, the digital and rather innovative Mobile Instant Messaging Interview (MIMI) method was also used and adapted to the content of the study. This was found to be suitable and provided a more personal insight into daily life. The ability to share pictures, videos and audio recordings of participants' daily challenges was found to be beneficial and provided a broader data base to be evaluated.

5.4.3 City Walks and integrated participatory tools

Accompanying people along everyday routes gave participants the opportunity to draw attention to specific areas, to reflect on their own behaviour and possibly to directly address deficits in the local infrastructure. It can be said that the method of participant observation can be usefully integrated into participatory processes of urban development, as it creates a situation close to the citizens that allows interaction at eye level (Reinharz 2017). In practice, however, this has also been associated with difficulties in some situations: e.g., personal mobility restrictions have an impact. In addition, vulnerable people were often strongly influenced by their daily condition. For example, they may be able to go for a walk on some days because of mild symptoms, but not on others. This has led to a number of cancellations or even to the walk being restructured into simple conversations tied to a specific location. It is also worth noting that the ability to concentrate, perform and assimilate can be severely impaired, particularly in the case of people with chronic illnesses and advanced age, which affected the productivity of the discussion but also underlined the need to make these people heard. Furthermore, it was ethically unacceptable for vulnerable people to go for a walk on hot days. The weather and temperature conditions on the selected days may therefore also have influenced the statements about hot days if people were not in a comparable situation. For parents with young children, who may be more likely to attend on hot days, the issue of external childcare during attendance was often raised.

The hotspot mapping tool has proven to be particularly useful in targeting people with limited mobility. This has enabled a more thorough understanding of the residents' awareness regarding the issue, which in turn enhances awareness concerning the health risks associated with heat waves. These information serves to augment the input for the routing application and city administration.

The implementation of the photo-voice method proved to be more complex and less efficient in terms of the intended results. Many heat-related aspects that were visible in the photos had already been mentioned during the discussions or hotspot mappings.

5.4.4 Measurements and modelling

Temporary meteorological measurements provided current or typical (limitedly representative) snapshots of the microclimate at selected locations and associated biophysical stressors. To identify or weigh up different adaptation options, models have been used to quantify the impacts.

ENVI-met was used to test the developed climate adaptation measures for their potential impact. The purpose of the modelling was to capture the differences between possible scenarios and to identify the most effective measures (Liu et al. 2021). This has proven to be a powerful tool for modelling the application of specific heat mitigation measures in selected areas and quantifying their impact on the thermal structure. These results also provided direct impulses for urban planning. Due to limited resources and time constraints, we were only able to examine subspaces. Comparing the current state of heat stress modelling with the individual perception and location of heat hotspots, as well as the analysis in the urban climate report, we observed clear similarities. Had we expanded our modelling to cover the entire city, we could have provided a more detailed assessment of these similarities and deviations.

When modelling using ENVI-met, it is also important to consider that the assumptions are based on a healthy, middle-aged man. However, this does not align with the needs or physical requirements of vulnerable groups. Currently, there is a shortage of adequate models and they need to be created and tested due to the varying levels of vulnerability characteristics. Utilising agent-based models as described as follows may serve as an alternative as long as appropriate characteristics are included.

Basically, different types of models can be distinguished. Two of them are particularly relevant in this context: Physical models based on partial differential equations, such as ENVI-met (Huttner & Bruse 2009, Salata et al. 2016, Tsoka et al. 2018), to study and quantify the effects of e.g., structural changes on microclimatic conditions, and agent-based models to study how individuals move in the city under the influence of heat and what stress they experience. As human perception of thermal comfort can vary greatly (Bittner & Stössel 2012), agent-based modelling could be a further step to complement on-site measurements or heat adaptation modelling results with additional information (Lee & Malkawi 2013). In contrast to measured or modelled meteorological variables (e.g., by using ENIV-met), agents have a 'sense of reason' in addition to their heat perception, e.g., they seek shade when their individual threshold of heat stress is reached. The heat sensation of a real person, e.g., when moving from the shade to the sun, is not immediate but delayed. The adaptation time of the body is too short to experience the maximum level of thermal stress in the sun (Jia & Wang 2021, Lee & Malkawi 2013). The knowledge gained from agent models could therefore be used to improve the location and spatial extent of recreational areas in cities (e.g., shade) (Lee & Malkawi 2013, Jia & Wang 2021).

5.4.5 Implications for policy makers

In addition to the assistance offered by the routing tool at an individual level, which indicates perhaps previously unknown, low-heat-stress routes and locations, and by promoting awareness, the application displays areas of higher heat stress, and therefore areas that should be prioritised for adaptation and cooling measures. The supplementary data which complement the routing (insights into individual behaviour, perceived problems, risk assessment, etc.) are useful for personal assessment and adaptation as well as for policy makers to target information to the population. Furthermore, routing can serve as a decisive tool to assess the absence of green space connections, areas where the public transport system requires upgrading, and when amenities like road layouts or traffic signals need adjusting to circumvent prolonged waiting times in areas lacking shade. Additionally, it can identify where population-restricted spaces require urban renewal due to limited and pressurised urban space.

Heat-avoiding routing serves as a useful and easily accessible tool in fighting heat stress and adapting to the effects of rising temperatures. However, to fully address the challenge of increasing overheating in urban areas, it is necessary to expand the implementation of other measures that complement the use of heat-avoiding routing. Table 1 includes adaptation measures that have positive impacts on the health and mobility of the urban population. Examples comprise green space networking, unsealing, and creating pocket parks. Furthermore, these measures provide co-benefits such as enhancing the urban design and perception of public spaces (e.g., feeling of security) or improving air quality. Our surveys have revealed other measures that can be implemented in the short term, including installing drinking water fountains in public spaces and providing additional shaded seating.

Consistent planning and implementation of corresponding measures, which require construction and are therefore time-consuming, must be ensured in all areas. Furthermore, our findings indicate that by providing targeted information and facilitating participation, the public's awareness of heat stress risks can be broadened and reinforced, leading to a reduction in healthcare system burden.

6 Conclusion and outlook

The results provided valuable insights into the spatial distribution of heat hotspots and the evaluation of data obtained through a holistic inter- and transdisciplinary approach aimed at addressing the significant challenge of mitigating urban heat loads through co-design strategies. An assessment of the perspectives of experts and people at risk showed that heat stress is increasingly perceived and that the risk of heat stress is underestimated by the majority of people. Current adaptation measures are partly in place or planned, but not (yet) consistently implemented at community and individual level. This was shown by the modelling of heat hotspots in the current state and by comparing it with the potential for microclimatic improvement through a modelled adapted state. In addition, the behavioural patterns of the study participants have not yet consistently adapted to the changing thermal conditions in the urban area, and the need for heat adaptation measures varies across the general population and within vulnerable groups. Dynamic, heat stress-avoiding routing can be an important adaptation tool, with the help of factor weighting adapted to target groups. At the time of publication, the routing service prototype was undergoing initial user tests. The results showed that the approach was suitable and achieved the goal of broad accessibility. Participants in the study described the heat stress avoidance routing as a helpful tool, but would also like to see further measures taken at the local level, such as the widespread installation of drinking water dispensers in public spaces and the provision of shaded seating. However, further intensive testing is required to confirm these initial indications and finalize the tool. To enhance heat-avoiding routing, it is advisable to increase green spaces, interconnect them, furnish shaded seating arrangements in public areas and simplify access to cool places, for instance, churches. These measures ought to be incorporated in a heat protection framework and implemented on the community level through heat action plans. The project's varied outcomes are a vital driver for Heidelberg's heat action plan and symbolize a tangible adaptation measure, collaboratively designed by citizens and endorsed by the municipality.

In a forthcoming study, we will assess the efficacy of routing and its impact on physical parameters during active use. By combining route parameters with health data, we can identify associations and gain a deeper comprehension of heat stress in diverse personal and external conditions.

The pilot study by Foshag et al. (2020), demonstrated that scientific findings intended to influence administration, policy and citizens and have a transformative effect require a certain amount of time. It cannot be assumed that scientific results will have an immediate and direct impact on practice and be implemented promptly. This is partly due to the different practical conditions and hurdles that can be minimised through transdisciplinary design, and likewise due to different capacities and time horizons that cannot always be planned for. A transdisciplinary approach such as the one pursued here, which aims at trusting cooperation with municipal stakeholders and intensive interaction with the population, can accelerate change processes and should, in our view, be consistently pursued. The combination of bottom-up and top-down approaches can promote transformative action and development (European Environment Agency 2016, Hermansen & Sundqvist 2022).

Some of the recommendations proposed by Foshag et al. (2020) to maintain the viability of public spaces in the face of increasing heat stress have been implemented in the context of the Heat Action Plan of the City of Heidelberg, published in 2022. It can be assumed that as the plan is gradually implemented, other measures that are necessary and desired by the population will be implemented in the near future and will lead to a more heat-adapted city area.

To broaden the scope of research and generate more comprehensive outcomes, citizen science practices could be implemented. Enthusiastic amateurs can partake in research activities depending on their level of involvement and the project format. Their contributions could range from data collection to active participation in co-designing processes for problem-solving solutions. This level of involvement corresponds to a transdisciplinary research approach.

Declaration of authorship

KF wrote the manuscript and was involved in the implementation of the individual methodological steps. JFu and CL discussed the results in terms of applicability and implementation in the technical context. JFa provided relevant practical perspectives and actively supported the project as a practice partner in the different phases. MB, PB and SR contributed to the results through selected methodological steps, which were included in the overall evaluation. NA co-developed the transdisciplinary study design. JFu, CL, JFa, SL, NA and AZ revised the manuscript. KF, JFu, SL, NA and AZ contributed to the idea and aims of the study. All authors have reviewed the manuscript and agreed to its submission. Correspondence and requests for material and data should be addressed to Kathrin Foshag.

Acknowledgements

We would like to thank the Baden-Württemberg Foundation for funding the HEAL project as part of the research programme "Innovations for Adaptation to Climate Change". Many thanks to all students who were actively involved in the project as student assistants and graduands Laura Pfisterer, Maximilian Schäfer and Janina Schüssler, as well as the co-supervisors of the theses, Prof. Dr. Tabea Bork-Hüffer, Jun.-Prof. Dr. Anna Growe, Dr. med. Alina Herrmann and Dr. Lina Pranaitytė for their enthusiastic support. We would also like to thank all the practice partners and participants who invested their valuable time and effort in the project and on whose input and commitment the results are based. SL and CL acknowledge support by the Klaus-Tschira Foundation. Special thanks to Lena Hertenstein for proofreading the manuscript

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Appendix

Tab A1: Overall Target Group Interaction. The table presents a synopsis of the methods employed and the participatory structure, along with their specific objectives, stakeholders or groups included, time / duration of implementation, and corresponding number of cases. The methodology is an interactive, transdisciplinary research design tailored to the research objective.

METHOD	FORMAT	FOCUS	TIME	CASES
Surveys	• personal		September 2021	50
	• online		September 2021	69
	• online		July-August 2022	88
	• online		June-August 2022	629
Interviews	• Interviews with vulnerable people		January 2022	4
	• Expert interviews (city administration)		January-March 2022	11
	• Interviews with vulnerable people		July-August 2022	8
	• Mobile Instant Messaging Interviews (MIMIs)		July-August 2022	8
	• Expert interviews (health experts)		August-September 2022	4
Interactive city walks	• Multi-methods-design (e.g. interactive mapping, participating observation)		July-September 2022 July-August 2023	4

Older people
Families
Cyclists and Pedestrians
People with pre-existing conditions
Pregnant women
Experts
General public

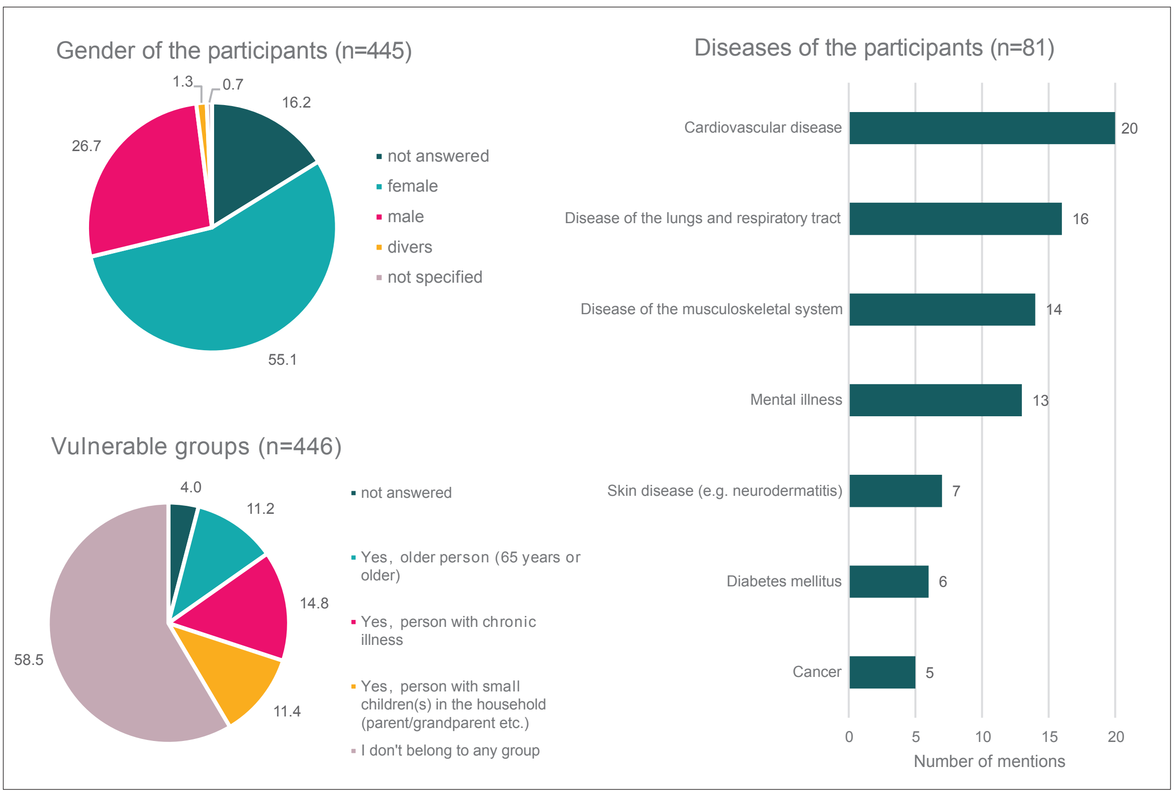

Fig. A1: Participant analysis of the online survey in summer 2022. The analysis shows the gender and vulnerability distribution of the participants and in addition the mentioned diseases of individuals that indicated a chronic illness. The survey provided a general overview; with several methods we focused on various vulnerable groups in detail (interviews with older people, MIMIs with pregnant woman, city walks with participants suffering from mental health issues).

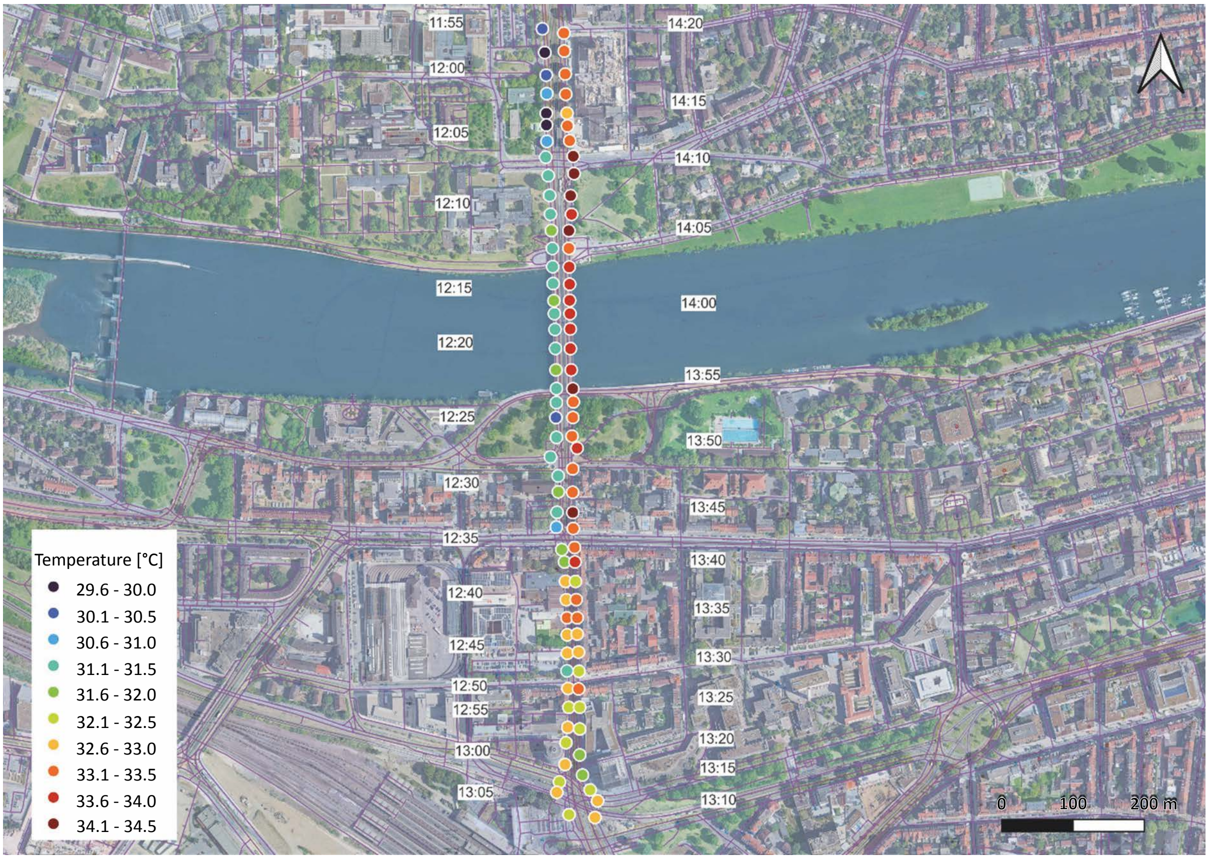

Fig. A2: Example of the on-site measurement data at Heidelberg, Bergheim along 'Mittermaierstraße'. Results show the overheating of the central city area and the dynamic temperature profile during midday on a heat day in July 2022.