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Rethinking urban heat stress: Assessing risk and adaptation options across socioeconomic groups in Bonn, Germany

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ABSTRACT

With climate change and socioeconomic trends expected to exacerbate the risk of urban heat stress, implementing adaptation measures is paramount to limit adverse impacts of heat on urban inhabitants. Identification of the best options needs to be based on sound, localised assessments of risk, understood as the interaction of hazard, exposure and vulnerability. Yet a review of the literature reveals that minimal research to date considers the perceived impacts of heat among urban residents. Based on a household survey in Bonn, Germany, this paper adopts an integrated approach to assess how different socioeconomic groups are affected by heat stress and explores the connections between perceived impacts of heat and indicators of exposure and vulnerability across groups. Results indicate that all socioeconomic groups are at risk of urban heat stress, though to differing extents and for different reasons. Exposure was found to be lowest in groups typically considered to be of higher risk, such as older respondents, who at the same time have the highest susceptibility. Students and other younger respondents, on the other hand, face comparably high exposure and have the lowest coping and adaptive capacities. At the same time, each group has its own capacities with the potential to mitigate risk. The study shows that urban inhabitants beyond "classic risk groups" usually addressed in literature and policy are affected by heat stress in ways that may not be accounted for in current urban policy.

1. Introduction

Climate change negatively impacts human health and well-being (Gasparrini et al., 2015; Estoque et al., 2020). Ongoing urban expansion and densification together with socioeconomic trends such as demographic ageing are adding to these impacts and particularly exacerbate the risk of urban heat stress.

Temperature increases are particularly manifest in cities due to the combined effects of climate change and the Urban Heat Island phenomenon (Estoque et al., 2020), which leads to higher probability and severity of extreme heat events (Hintz et al., 2018; Ellena et al., 2020), with potentially health-damaging or even deadly impacts (Gasparrini et al., 2015). However, the impacts of heat events do not only depend on the climate but are also influenced by demographic and social factors (Ellena et al., 2020). Important factors

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that have been linked to higher rates of heat stress and mortality (Oleson et al., 2013; Arbuthnott et al., 2016) include having certain health conditions or belonging to a specific age group, such as elderly (Arnberger et al., 2017; Lapola et al., 2019; Zemtsov et al., 2020) and young children (Bhattacharjee et al., 2019), or to marginalised groups, e.g. migrants or people living in poverty (Chow et al., 2012; Zemtsov et al., 2020).

In our view, focusing either solely on the environment or on demographic and social factors does not sufficiently capture all elements that contribute to risk of heat stress. Thus, in line with recent evolutions in thinking about risk, this paper adopts an integrated perspective that considers risk to be driven by the interplay of various political, environmental, economic and social factors (Turner et al., 2003; Birkmann et al., 2013; IPCC, 2014). Specifically, this paper follows the conceptualization proposed by IPCC (2014), in which risk results from the interaction of hazard, exposure and vulnerability (drawing on earlier work by Wisner et al. (2004) and others). The separation highlights the fact that risk is not driven by environmental hazards alone, but is rather the result of complex interactions between hazard and a population's dynamic exposure and vulnerability. In this paper, hazard refers to possible occurrence of physical events with the potential to adversely impact human health, while exposure is defined as human presence in places subject to hazards, or where hazard conditions may occur. Vulnerability is considered the predisposition to suffer adverse impacts; it includes susceptibility and lack of coping and adaptive capacities (IPCC, 2014). Looking at the risk of heat stress through this frame, it becomes clear that vulnerability is not merely a consequence of urban temperatures, but is produced in and by society (Ellena et al., 2020) and therefore has many facets.

To date, numerous studies analysing urban heat risk have been conducted. However, most of them either have a strong focus on the hazard component, e.g. assessing magnitude and frequency of (future) extreme heat events or diving into specific aspects of vulnerability (Aubrecht and Özceylan, 2013), such as heat susceptibility related to health conditions (Maller and Strengers, 2011; Estoque et al., 2020). Since impacts of heat events depend on the interplay of the built environment and climatic, institutional, social and economic factors (Ellena et al., 2020), research on heat should include a broader portfolio of future-oriented and context-specific urban development analyses (Leal Filho et al., 2018).

Overall, it is striking that relatively little research focuses on assessments that consider, compare, or weigh a broad range of heat risk factors such as health, behaviour, age, economic or housing conditions. Accordingly, there is little research on the development of analytical risk assessment frameworks for urban or sub-urban scales. In our view, studies of urban heat must broaden their focus beyond such groups by also considering habits, qualitative perceptions and experiences in different urban surroundings (Abusaada, 2020). To allow for assessing overall risk from heat stress, all components of heat need to be looked at in a comprehensive study. To fill this gap, our study surveys households to understand how contextual factors such as housing characteristics and climatic factors interact with individual factors such as attitudes and awareness of urban dwellers. Even in well-researched areas like European cities where impacts of heat are projected to increase in the future (Guerreiro et al., 2018), no such analytical risk assessment framework exists. This is even despite the record hot summers of 2018 and 2019 (Sousa et al., 2019), which triggered research into possible adaptation measures (Beckmann and Hiete, 2020). Based on a household survey in the city of Bonn, Germany, under the umbrella of a larger research project on Future-oriented Vulnerability and Risk Analysis as an Instrument to Support Urban Infrastructure Resilience (ZURES), and supplemented by literature searches, this study aims to answer the following questions:

1) What is the state of urban heat risk assessments outlined in the literature and how are risk components commonly assessed?
2) In their own perception, how are different socioeconomic groups affected by heat stress?
3) Why are they affected differently and what kind of underlying factors can be identified?
4) What conclusions can be drawn for urban heat risk assessments, planning and management, both in Bonn and beyond?

2. Background: Urban heat and heat stress

2.1. Urban heat risk assessments: Concepts and research gaps in global literature

Simply knowing which urban zones are hotter or cooler does not provide sufficient information on which areas to target in the future (Verdonck et al., 2018) or which interventions are most promising. Gaining such understanding requires studying individually experienced heat exposure as well as assessing individual or group vulnerability, including susceptibility, coping and adaptive capacities. Studying heat stress on this level is challenging, and hence has only been undertaken in a handful of studies (Hoehne et al., 2018).

A structured SCOPUS search (TITLE-ABS-KEY ("urban heat") AND TITLE-ABS-KEY (susceptibility OR "adaptive capacity" OR "coping capacity")) yielded 39 results. The 39 papers can be divided into 3 main groups, a first one focusing on climatic aspects and refined modelling of urban thermal characteristics (Levy et al., 2008; Górka-Kostrubiec et al., 2012; Krüger et al., 2013; Huang et al., 2014) and a second group with a focus on urban patterns, including analyses of selected spatial, building, and/or population distribution aspects (Wilhelmi and Hayden, 2010; Chow et al., 2012; Fischer et al., 2012; Gunawardena and Steemers, 2019; Khan et al., 2020). This group also comprises papers exploring the role of urban form on local thermal environments (Mehrotra et al., 2018; Voelkel et al., 2018; Xu et al., 2019) including recommendations on improved design (Cetin, 2015; Csete and Buzasi, 2016) or greening (Weber et al., 2015; Arnberger et al., 2017) and urban green infrastructure (Cetin, 2015; Arnberger et al., 2017; Sharma et al., 2018; Lewis et al., 2019).

The third group focuses on aspects related to urban population patterns, including papers dealing with health and heat-related mortality rates (Wilhelmi and Hayden, 2010; Kovats, 2013; Oleson et al., 2013; Arbuthnott et al., 2016; Milojevic et al., 2016) perceived and absolute impacts of urban heat on vulnerable populations (Akerlof et al., 2015; Hoehne et al., 2018; O'Lenick et al.,

Table 1
Indicators used to assess urban heat (across papers from literature survey).

	Exposure		Susceptibility / sensitivity / sensibility		Coping capacity		Adaptive capacity	
	Source		Source		Source		Source	
Population density	x	Zemtsov et al., 2020	x	Zhang et al., 2019, Krüger et al., 2013			x	Xu et al., 2019
Household size							x	Arnberger et al., 2017
Age/age group	x	Hoehne et al., 2018	x	Bhattacharjee et al., 2019, O'Lenick et al., 2019, Wilhelmi and Hayden, 2010				
Elderly people (number, spatial distribution, living alone, capacities)	x	Lapola et al., 2019	x		x	Zemtsov et al., 2020	x	Chow et al., 2012, Voelkel et al., 2018, Arnberger et al., 2017
Gender	x	Hoehne et al., 2018	x	O'Lenick et al., 2019, Akerlof et al., 2015				
(Household) income/ poverty/resources	x	Hoehne et al., 2018	x	Akerlof et al., 2015, Weber et al., 2015	x	Zemtsov et al., 2020	x	O'Lenick et al., 2019, Voelkel et al., 2018, Chow et al., 2012
Education			x	Akerlof et al., 2015, Weber et al., 2015			x	Voelkel et al., 2018
Household-level knowledge, attitudes and practices							x	Wilhelmi and Hayden, 2010, O'Lenick et al., 2019
Social capital, community stability/facilities			x	Wilhelmi and Hayden, 2010			x	Leal Filho et al., 2018, Wilhelmi and Hayden, 2010, O'Lenick et al., 2019
Public awareness/ availability of information on heat waves							x	Zhang et al., 2018, Zhang et al., 2019
Average of low English proficiency population							x	Voelkel et al., 2018
Race/minorities	x	Hoehne et al., 2018	x	O'Lenick et al., 2019, Akerlof et al., 2015			x	Leal Filho et al., 2018, Voelkel et al., 2018
Migrant population			x	Zemtsov et al., 2020			x	Chow et al., 2012
Health status			x	O'Lenick et al., 2019, Arnberger et al., 2017, Akerlof et al., 2015, Wilhelmi and Hayden, 2010				
Disabilities			x	Akerlof et al., 2015				
Human Development Index (HDI)							x	Lapola et al., 2019
Climate pattern								
Average/maximum temperature (in a given area)	x	Bhattacharjee et al., 2019, Chow et al., 2012, O'Lenick et al., 2019, Zhang et al., 2018	x	Krüger et al., 2013				
Heat wave (occurrence/ duration)	x	Zhang et al., 2019, Wilhelmi and Hayden, 2010, Weber et al., 2015						
UHI/heat distribution	x	Akerlof et al., 2015, Wilhelmi and Hayden, 2010, Voelkel et al., 2018						
Outdoor air pollution	x	O'Lenick et al., 2019						
Urban pattern/perception								
Urban land use/building patterny	x	Wilhelmi and Hayden, 2010, Zhang et al., 2019	x	Zhang et al., 2018, Krüger et al. 2013			x	Xu et al., 2019
Urban compactness/ contiguity							x	Xu et al., 2019
Engineered infrastructure and healthcare availability/ accessibility							x	Leal Filho et al., 2018, Bhattacharjee et al., 2019, Xu et al., 2019, Zhang et al., 2019, Zhang et al., 2018
Accessibility of public heat refuges	x	Voelkel et al., 2018						
			x	Weber et al., 2015			x	

(*continued on next page*)

Table 1 (*continued*)

	Exposure		Susceptibility / sensitivity / sensibility		Coping capacity		Adaptive capacity	
		Source		Source		Source		Source
House conditions/ quality/perception								Bhattacharjee et al., 2019, Voelkel et al., 2018
Satisfaction/perception of apartment/ surroundings	x	Arnberger et al., 2017						
Apartment size	x	Arnberger et al., 2017						
Air conditioning/cool space	x	Arnberger et al., 2017, Voelkel et al., 2018						
Urban cooling/greening measures							x	Weber et al., 2015
Vegetation and green space patterns/use	x	Chow et al., 2012			x	Arnberger et al., 2017	x	Bhattacharjee et al., 2019, Xu et al., 2019, Zhang et al., 2018
Paved areas			x	Zhang et al., 2019				

2019) or with individual and household capacities, perceptions and adaptation strategies (Mahlkow et al., 2016; Ogato et al., 2017; Voelkel et al., 2018). Overall, surprisingly little research is available on understanding the impacts of heat on a more granular urban scale (Voelkel et al., 2018) like neighbourhoods or households. Social and behavioural factors and their impacts on the effects of urban heat still remain underexplored (Lapola et al., 2019; O'Lenick et al., 2019).

With respect to the indicators used in the different assessments, there is hardly a clear picture. Some studies make use of indicators to assess exposure, vulnerability or related coping and adaptive capacities, with indicators that can be divided into groups describing population, climate or urban patterns. However, the indicators used vary widely across these domains (see Table 1). The same is true for susceptibility, sensitivity and sensibility—the actual use of the terms varies across publications. One commonality is that indicators related to outdoor or indoor climate are mostly used to assess exposure. The picture for indicators related to population or urban patterns is less clear as population density, age, race and poverty or income are frequently used as indicators across categories. Only little research is available on perceived impacts of urban heat, including on health (Akerlof et al., 2015); if this topic is addressed at all, it is mostly in the context of groups pre-identified as vulnerable, mostly senior citizens, ignoring other groups that may also be highly vulnerable. Another critique of urban heat vulnerability assessments is that their calculations are mostly based on census data at the risk of leaving out important factors on which data is unavailable (Zhang et al., 2018).

Unsurprisingly, different publications find heat vulnerability assessments and the selection of indicators still in the early stages of development (Zhang et al., 2018) and stress the importance of an improved understanding of patterns of urban heat vulnerability (Weber et al., 2015; Lapola et al., 2019; Zemtsov et al., 2020) in transformative and interdisciplinary approaches (Wilhelmi and Hayden, 2010; Filho et al., 2019) for developing context-specific adaptation actions and supporting urban decision-making.

2.2. *Urban heat stress in Germany*

Comparable to the growing global body of literature, the number of publications on urban heat in Germany has grown considerably in the past years. Modelling approaches for measuring impacts of climate change on extreme heat make up a large part of the publications, e.g. studies on the effects of extreme heat in Rostock (Richter, 2016), spatial patterns of UHI intensity in Augsburg (Straub et al., 2019), downscaling of UHI in Hamburg (Hoffmann et al., 2018), quantification of surface (Li et al., 2018b) and subsurface (Menberg et al., 2013) UHI intensity in Berlin and other German cities up to geothermal potentials of UHI in Cologne (Zhu et al., 2010) and the interlinkages between heat and pollution (Li et al., 2018a), water quality or temperature, e.g. in Oberhausen (Müller et al., 2014) and Cologne (Zhu et al., 2015).

Another group of publications focuses on urban planning and improving existing urban patterns or policies. Papers in this category increasingly deal with the benefits of green-blue infrastructure for reducing heat impacts, e.g. in studies on the bioclimatic situation in the city of Dresden (Krüger et al., 2013), thermal benefits of urban trees in Dresden and other European cities (Helletsgruber et al., 2020), or cooling effects of urban gardens in Berlin (Rost et al., 2020). Related publications consider suitable governance and urban decision-making for adapting cities to heat, among others by means of assessments of urban climate and risk governance and related planning processes in Berlin (Mahlkow et al., 2016; Mahlkow and Donner, 2017), or developing methods to estimate the impacts of current land use and spatial planning policies on local climate regulation in Leipzig (Schwarz et al., 2011). However, while many German cities have adopted climate change adaptation plans or are in the process of doing so, reducing risk from urban heat still receives comparably little attention (Donner et al., 2015; Mahlkow and Donner, 2017).

Even less attention is paid to urban inhabitants' perception of heat and its impacts on individual adaptation and coping; the few studies conducted in Germany focus either on thermal comfort in general, e.g. the thermal atmosphere in Stuttgart (Ketterer et al., 2013; Ketterer and Matzarakis, 2015) or on health impacts, e.g. on predictors of health-related heat risk perception of urban residents of Augsburg (Beckmann and Hiete, 2020). Broader studies across societal groups and vulnerability factors remain a blind spot in the literature.

In general, both the review of global assessments as well as the overview of papers published on Germany reveal that few studies go

beyond assessments of the built environment and health-related analyses of impacts. Focus still often lies on single factors like impacts of heat on health, or on specific socioeconomic groups, mostly elderly or young children, despite the fact that urban heat affects all socioeconomic groups. Therefore, in our view, broader studies of urban heat are needed that consider, among other aspects, individual factors such as experiences, habits, and risk perception in different urban environments (Abusaada, 2020). More research is required to uncover the diverse impacts of urban heat beyond simply linking exposure to health and characteristics of the built environment. Such efforts to analyse and link the different components of urban heat risk can support urban decision-making and allow for tailoring of group-specific adaptation measures (Wolf et al., 2015; Ellena et al., 2020).

3. Materials and methods

3.1. Survey area and methods

The city of Bonn increasingly faces climatic and sociodemographic pressures that contribute to growing heat stress. The city is characterized by considerable population growth (Bundesstadt Bonn, 2020c) expansion of residential and commercial areas and sealing of undeveloped spaces. In addition, Bonn exhibits comparatively high air temperatures, which are trending upwards. Its 10-year average temperature increased from 9.6 °C between 1885 and 1904 to 11.4 °C between 2005 and 2014 (Bundesstadt Bonn, 2020). In comparison, the average temperature in Germany between 2005 and 2014 was 9.3 °C (Statista, 2020). The average annual number of days in Bonn with a maximum temperature over 25 °C has increased from 37 days over the 1961–1990 period to 48 days in the 1989–2018 period. Temperatures in Bonn city centre are, on average, 8 °C higher than surrounding areas (Stadt Bonn, Amt für Umwelt, Verbraucherschutz und Lokale Agenda and GEO-NET Umweltconsulting GmbH, 2020).

Bonn has around 333,000 inhabitants (Bundesstadt Bonn, 2020c). Overall, 18% of the total inhabitants are 65 years or older, with the percentage expected to grow to 22.4% by 2030 (Bertelsmann Stiftung, 2020). The city is also characterized by a comparably high birth rate of 10.7 per 1000 residents, resulting in many families with young children, which is predicted to remain relatively stable (Bertelsmann Stiftung, 2020). In- and out-migration stands at 94 and 85 respectively per 1000 people in 2018, with the highest share in the age group between 18 and 30 (Bertelsmann Stiftung, 2020). One reason for this is the comparatively high number of students. The approximately 35,000 university students in Bonn (Universität Bonn, 2020) account for around 10% of urban inhabitants. More than half of the city's total population lives in single or couple households (Bundesstadt Bonn, 2020e), making such households particularly relevant for assessing heat stress in Bonn. The city contains some large green areas, however their accessibility differs across the city and is particularly low in the densely built-up inner-city areas.

To study risk of heat stress in Bonn, a bottom-up risk assessment approach was chosen, focusing on the causes of heat stress risk rather than focusing on the heat hazard itself (GIZ and CCA RAI, 2014). Therefore, the assessment mainly considered patterns of vulnerability and exposure while not covering specific hazard levels across the research area.

To learn more about residents' experiences with heat stress and efforts to cope and adapt, a household survey (following other research using household surveys to determine perceived heat stress, e.g. Akerlof et al., 2015; Arifwidodo and Chandrasiri, 2020) was conducted in areas that are characterized by high heat levels.

The survey was conducted in three statistical districts, "Vor dem Sterntor" in the city centre (8864 inhabitants), "Bad Godesberg Zentrum" and "Bad Godesberg Nord" (5603 and 1730 inhabitants, Bundesstadt Bonn (2020)) in the south of Bonn (Fig. 1). These districts are characterized by comparatively dense development in their cores. The selection of the districts was based on the results of the climate analysis carried out by GEO-NET in the ZURES project, which was able to forecast comparatively high and future increasing heat loads in both areas (Bundesstadt Bonn, 2020d). As a consequence, people living and working in these districts are directly exposed. However, it is important to mention that these districts are not representative of the entire city, since socioeconomic conditions vary significantly across districts in Bonn.

The survey was carried out from 22 May to 22 September 2018. This period was characterized by summer weather conditions, including several days with daily maximum temperatures of over 30 °C. These conditions are likely to have increased respondents' heat stress awareness and might thus have influenced survey responses. Responses were collected by 13 interviewers via a tablet-based, face-to-face survey at all residences and additionally in public spaces from residents living in the survey area districts. Not all households participated in the survey, but a total of 688 questionnaires were completed.

Besides basic socioeconomic factors, the survey consisted of 25 questions, some of which included sub-questions, to collect data on six thematic aspects: 1) general risk perception, i.e. which natural hazards—including heat waves—are perceived as problematic; 2) perception of heat in different places; 3) health problems perceived during periods of heat stress; 4) measures that households have already taken or are considering for the future to protect themselves against heat waves; 5) households' expectations of policymakers with regard to measures; and 6) the use of green spaces and their effects on perceived heat stress. The survey design was based on an initial literature review and meetings with representatives of the city administration, and was structured around an integrated understanding of risk and its components.

3.2. Categorization of socioeconomic groups

The risk assessment was structured around socioeconomic groups to identify differences in Bonn residents' exposure and vulnerability to heat. Respondents were classified into groups based on the most relevant influencing factors for heat stress as identified in literature. Sociodemographic factors specific to the study area—for example, Bonn's large number of students—were also considered to ensure the socioeconomic groups accurately reflected conditions in Bonn.

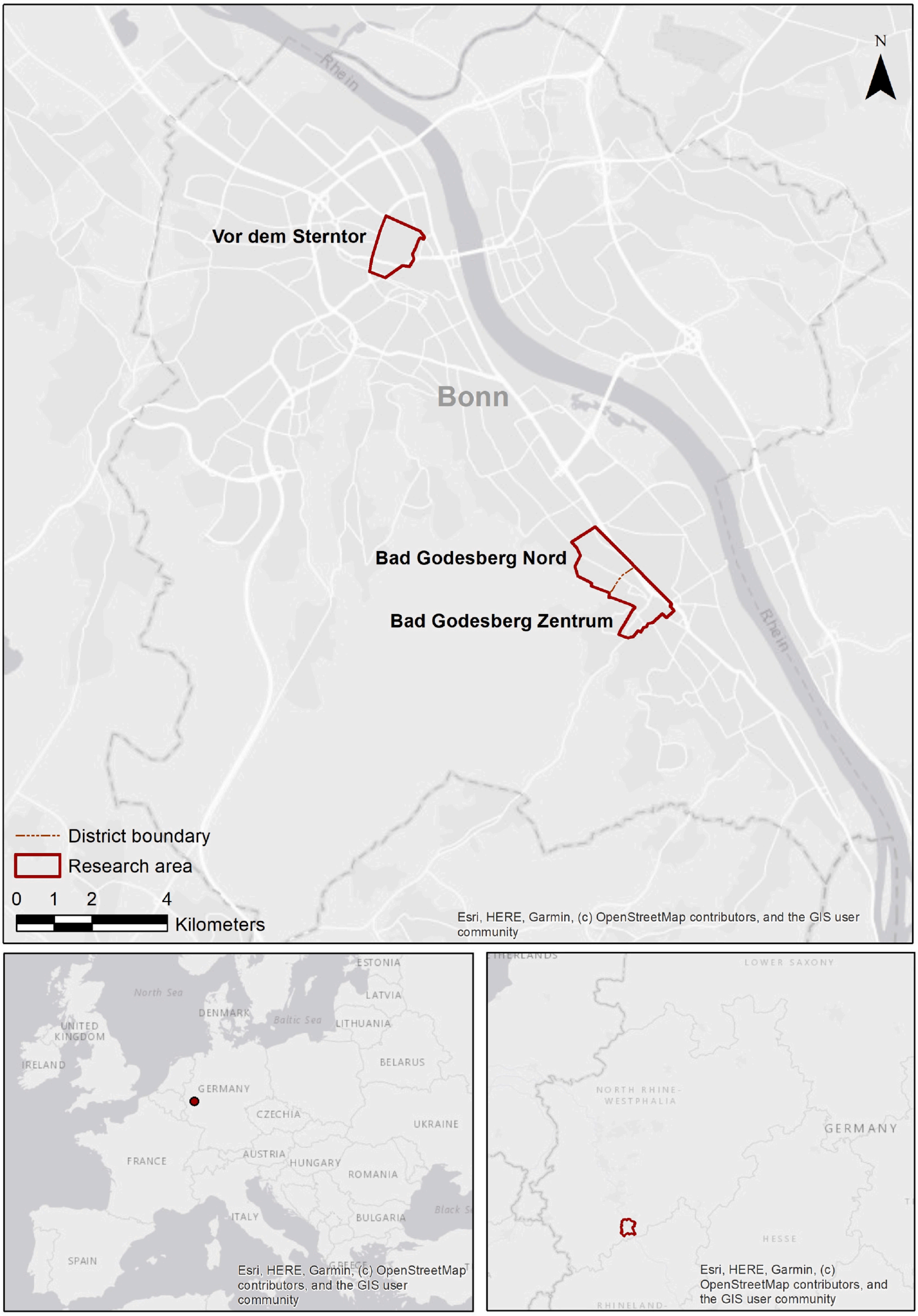
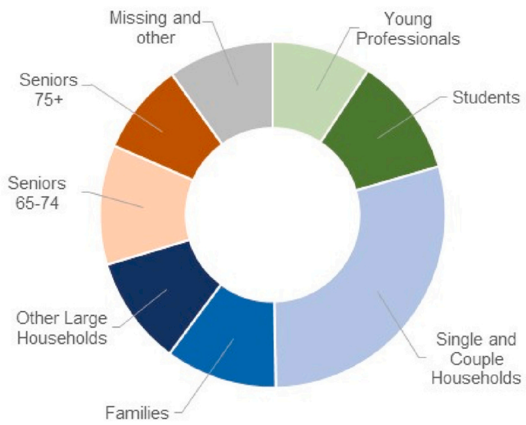


Fig. 1. Map portraying location of Bonn within Europe and the federal state of North-Rhine Westphalia (bottom maps) and location of survey districts (top) "Vor dem Sterntor" (north), "Bad Godesberg Zentrum" and "Bad Godesberg Nord" (combined, south) in the city of Bonn.

Socioeconomic groups



Group		Criteria	n	%
Age <30 years old			141	20.5%
Young Professionals	YP	>1500€ per month	64	9.3%
Students	STU	<1500€ per month, A-level+ education	77	11.2%
Age 30-64 years old			343	49.9%
Single and Couple Households	S&C	1-2 people	201	29.2%
Families	FAM	3+ people, including 1+ child <6 years	72	10.5%
Other Large Households	OLH	3+ people, no child <6 years	70	10.2%
Age >64 years old			136	19.8%
Seniors (65-74)	65-74	65-74 years	77	11.2%
Seniors (75+)	75+	75+ years	59	8.6%
Missing and other			68	9.9%
		Total	**688**	

Fig. 2. Overview of socioeconomic groups and respective categorization criteria and distribution.

Table 2
Overview of indicators chosen for the risk assessment.

Component	Indicator	Indicator Code	Survey question(s)	Relevant responses
Exposure				
	HHs living in attic stories	EXP1	Information about your house/apartment: I live in the attic story	% of respondents reporting "yes"
	Frequent user of public transportation	EXP2	To what extent do you agree with the following statements? I frequently use public transportation.	% of respondents reporting "yes"
	Lack of access to green space at home	EXP3	Information about your house/apartment: my apartment/house has a green balcony/terrace/ garden	% of respondents reporting "yes"; inverted
	Living space lacks cooling features	EXP4		Sum % of respondents reporting either EXP4.1 or EXP4.2 OR EXP4.1 and EXP4.2
	Living space lacks additional shading features	EXP4.1	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Additional shading e.g. with awnings or blinds	Sum % of respondents reporting "already implemented" and "in implementation"; inverted
	Living space lacks plants and water features	EXP4.2	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? trees/plants/water features in the garden/ courtyard/balcony	Sum % of respondents reporting "already implemented" and "in implementation"; inverted
	HHs who do not adapt their behaviour to heat	EXP5	Which of the following measures to protect against heat waves have you already implemented ormare you planning to implement? Adaptation of my behaviour (e.g. working hours, meeting points, sleep, choice of transport mode)	Sum % of respondents reporting "already implemented" and "in implementation"; inverted
	OVERALL EXPOSURE	Average of EXP1, EXP2, EXP3, EXP4 and EXP5		
Vulnerability				
Susceptibility	HHs with people in need of care and/or suffering from chronic diseases	SUS1		Sum % of respondents reporting either SUS1.1 or SUS1.2 OR SUS1.1 and SUS1.2
	HHs with people suffering from chronic diseases	SUS1.1	How many ill people or people in need of care are living in your household? People suffering from chronic disease (e.g. cardiovascular disorders, diabetes)	Sum % of respondents reporting "applies for me personally" and "applies for one or more household members (not including myself)"
	HHs with people in need of care	SUS1.2	How many ill people or people in need of care are living in your household? People in need of care (e.g. mobility impairment and/or communication impairment, dementia)	Sum % of respondents reporting "applies for me personally" and "applies for one or more household members (not including myself)"
	HHs with small children	SUS2	Out of all the people living in your household, how many are children under 6 years?	Sum % of respondents reporting "1", "2", "3", "4 or more"
	HHs with elderly members	SUS3	Out of all the people living in your household, how many are older than 65 years?	Sum % of respondents reporting "1", "2", "3", "4 or more"
	OVERALL SUSCEPTIBILITY	Average of SUS1, SUS2 and SUS3		
Lack of Coping Capacity	HHs who are unable to cool living space	COP1		Sum % of respondents reporting either COP1.1 or COP1.2 OR COP1.1 and COP1.2
	HHs unable to ventilate their living space	COP1.1	Information about your house/apartment: I can ventilate my apartment (i.e. generate a cross breeze)	% of respondents reporting "yes"; inverted
	HHs without air-conditioning system	COP1.2	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Installation of an air-conditioning system	Sum % of respondents reporting "already implemented" and "in implementation"; inverted
	HHs living far from parks	COP2	There are sufficient green and recreational areas in the immediate vicinity of my place of residence (max. 300 m radius)	Sum % of respondents reporting "Absolutely agree" and "More likely to agree"; inverted
	HHs who are new to Bonn or to their current residence	COP3		Sum % of respondents reporting either COP3.1 or COP3.2 OR COP3.1 and COP3.2
	HHs who are new to Bonn	COP3.1	How long have you lived in Bonn?	% of respondents reporting "less than 1 year"
	HHs who are new to their current residence	COP3.2	How long have you lived in your current residence?	% of respondents reporting "less than 1 year"
	HHs who are unable to rely on neighbors or family/ friends for help	COP4		Sum % of respondents reporting either COP4.1 or COP4.2 OR COP4.1 and COP4.2

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Table 2 (*continued*)

Component	Indicator	Indicator Code	Survey question(s)	Relevant responses
	People who are unable to rely on neighbors for help	COP4.1	In the event of a heat wave of over 30 °C over a period of at least 3 days, I would ask family/friends for help if necessary (e.g. when shopping or to spend the night there)	Sum % of respondents reporting "Absolutely agree" and "More likely to agree"; inverted
	People who are unable to rely on family/friends for help	COP4.2	In the event of a heat wave of over 30 °C over a period of at least 3 days, I would ask for help in my neighbourhood if necessary (e.g. when shopping or borrowing a fan)	Sum % of respondents reporting "Absolutely agree" and "More likely to agree"; inverted
	HHs who are dependent on aid organizations or the city for help	COP5		Sum % of respondents reporting either COP5.1 or COP5.2 OR COP5.1 and COP5.2
	People who are dependent on aid organizations or the city for help	COP5.1	In the event of a heat wave of over 30 °C over a period of at least 3 days, I would rely on aid organizations and rescue services (e.g. Malteser, ASB, Johanniter)	Sum % of respondents reporting "Absolutely agree" and "More likely to agree"
	People who are dependent on aid organizations or the city for help	COP5.2	In the event of a heat wave of over 30 °C over a period of at least 3 days, I would rely on authorities and state organizations (e.g. police, fire brigade)	Sum % of respondents reporting "Absolutely agree" and "More likely to agree"
	OVERALL LACK OF COPING CAPACITY	Average of COP1, COP2, COP3, COP4 and COP5		
Lack of Adaptive Capacity	HHs who do not consider heat a future threat	ADP1	Which of the following natural hazards will become problematic for you personally in the future (until 2030)? Heatwaves	% of respondents reporting "yes"; inverted
	HHs with no intention of adapting to heat	ADP2		Average of ADP2.1, ADP2.2, ADP2.3 and ADP2.4
	HHs with no intention of installing air conditioning	ADP2.1	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Installation of an air conditioning system	% of respondents reporting "I would implement with described change of the city climate until 2030"; inverted
	HHs with no intention of increasing shading	ADP2.2	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Additional shading e.g. with awnings or blinds	% of respondents reporting "I would implement with described change of the city climate until 2030"; inverted
	HHs with no intention to create green space	ADP2.3	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Trees/plants/water areas in the garden/Inner courtyard/Balcony	% of respondents reporting "I would implement with described change of the city climate until 2030"; inverted
	HHs with no intention to adapt behaviour	ADP2.4	Which of the following measures to protect against heat waves have you already implemented or are you planning to implement? Adaptation of my behaviour (e.g. working hours, meeting points, sleep, choice of transport mode)	% of respondents reporting "I would implement with described change of the city climate until 2030"; inverted
	Renters	ADP3	Information about your house/apartment: I live for rent	% of respondents reporting "yes"
	HHs with low level of income	ADP4	Monthly net household income in euros (income after deduction of all levies, taxes and compulsory insurance contributions)	Sum % of respondents reporting "less than 900€" and "900–1500€"
	People who are not willing to invest private money in adaptation	ADP5	I am willing to invest private money for the structural adaptation of my house/apartment to the described climatic changes.	% of respondents reporting "yes"; inverted
	OVERALL LACK OF ADAPTIVE CAPACITY	Average of ADP1, ADP 2, ADP 3, ADP 4 and ADP 5		

The categorization was conducted via a two-step approach. First, the population sample was sorted into three age brackets based on the indicated age of respondents: below 30 years, between 30 and 64 years, and 65 years or older. Following this initial division, further distinction was made using additional socioeconomic factors considered most relevant for heat stress risk of the respective age brackets. Respondents under 30 were divided based on income and education level as proxy indicators for students and young professionals; those aged 30–64 were divided based on household size and number of small children living in the household to distinguish among single and couple households, families, and other large households; and people over age 65 were divided into two smaller age groups. All respondents who provided complete demographic information were assigned to one of these socioeconomic groups. People who did not provide this information (68 respondents, 9.9% of the sample) could not be assigned to any group and thus were not further considered in the assessment. This left a final total of 620 responses included in the analysis. The categorization scheme, including groups, inclusion criteria and sample distribution, is illustrated in Fig. 2.

The study has some limitations with respect to data collection and analysis. While the categorization scheme does enable creation of internally homogeneous and externally heterogeneous socioeconomic groups, its reliance on proxies for group assignation may lead to some misclassification. For example, students with a high income or who are older than 30 years would not be assigned to the student group in this assessment. Additionally, further distinction was not feasible due to missing data for some relevant factors, such as income, for which relatively few respondents provided answers. Lastly, restrictive data protection regulations did not allow for a representative survey, however an attempt was made to give as accurate a picture of the quarters' sociodemographic structure as possible with the total number of answers, based on statistical data available. Additionally, some of the questions related to overall households might have been misunderstood, which is reflected in the discrepancy in reported age and reported count of elderly household members. Questions did not only cover individual aspects but also referred to household conditions, which is important to consider when interpreting the results. Lastly, the fact that the survey was carried out during a relatively hot period might have introduced bias. While such bias might have resulted in more nuanced responses, it also offers an advantage in that answers were collected while the problem was being perceived, not months later, by which time respondents may no longer remember heat impacts in detail.

3.3. Data analysis and interpretation methods

In order to identify how risk of heat stress varied across the identified socioeconomic groups, the survey data was analysed by applying descriptive statistics to identify representative health impacts and risk characteristics across groups (see Macfie and Nufrio, 2006). Descriptive statistics best fit the measurement scale of the survey data, which was primarily on an ordinal scale and thus did not allow for higher order statistical measures (Bortz and Schuster, 2010).

As elaborated in the introduction chapter, this study's risk conceptualization is rooted in the IPCC (2014) understanding of risk as the interaction of hazard, exposure and vulnerability. Following a bottom-up approach with the focus on vulnerability and exposure, the hazard component has not been further investigated. Hence, a detailed assessment of exposure and vulnerability was conducted. First, impacts of heat stress were outlined across groups. Common health impacts were analysed for the frequency of their reported occurrence in the different socioeconomic groups in Bonn. Next, patterns in exposure across groups were determined by analysing locations of highest perceived heat stress in Bonn. Differences in vulnerability across groups were analysed through the lens of its components, susceptibility, lack of coping capacity and lack of adaptive capacity.

To operationalize the risk components, indicators were developed based on the most important factors associated with heat stress (see Ch. 1) and relevant survey questions. An overview of the indicators and criteria is given in Table 2. Exposure and vulnerability (via its three subcomponents) are assessed with five indicators, except for the susceptibility subcomponent which comprises three indicators. Indicators of exposure were selected based on locations of highest perceived heat stress (as reported by survey respondents; EXP 1–2), features of the living space that affect felt temperature (EXP 3–4), and willingness to make behavioural adaptations (EXP 5) to capture how behaviour affects exposure. Susceptibility is determined by the number of individuals in a household that fall into groups with heightened vulnerability to heat as outlined in the literature (SUS 1–3). Indicators of lack of coping capacity address features of the living space that facilitate coping behaviours (COP 1–2), length of time living in Bonn or current residence (COP 3–4), and both access to and dependency on external help for coping (COP 5). Lastly, lack of adaptive capacity is based on risk awareness (ADP 1), willingness to adapt (ADP 2), and factors determining viability of adaptation measures for particular households (ADP 3–5).

For these indicators, specific criteria were derived from the responses. These criteria were designed as dichotomous variables (Lewis-Beck et al., 2004). The percentage of compliant respondents in each group was calculated and then compared to other groups. This means that the higher the share of complying respondents in a group, the higher the risk faced by this group based on the respective indicators.

As this study focuses on risk comparison across groups, normalization was applied for each indicator. Based on min-max normalization, the percentage of respondents complying with the defined criteria was rescaled to a value between zero (equalling minimum absolute value) and one (equalling maximum absolute value) (see OECD, 2008). Although the normalized values allow for comparisons across groups for each indicator, they cannot be easily compared across indicators and have thus not been aggregated to yield an overall value for the respective components or even risk. Instead, a further categorization into five qualitative classes, ranked from very low to very high, has been made, which allows for comparison across indicators in relative terms.

4. Results

4.1. Perceived physical and psychological impacts of heat

In total, 92.7% of survey respondents reported experiencing some type of health impacts during periods of heat exposure. Out of all the assessed health effects, lethargy (75.7%), difficulty sleeping (72.2%) and trouble concentrating (65.4%) were reported most often, while dizziness (37.1%), cardiovascular problems (35.8%) and nausea (12.1%) were less frequently reported (see Fig. 3).

Looking at the rates at which people reported experiencing any health impacts, there were clear differences across socioeconomic groups. For example, 100% of Students experienced at least one health impact, while 13% of Seniors 65–74 did not report any health impacts at all. In fact, with the notable exception of cardiovascular problems, Seniors 75+ were the most likely to report having never experienced health problems in connection with heat.

Though there are similar response patterns across socioeconomic groups when both "frequent" and "sometimes" responses are considered together, this changes when considering only the "frequent" responses. Fig. 3 shows distinct problem areas for the different

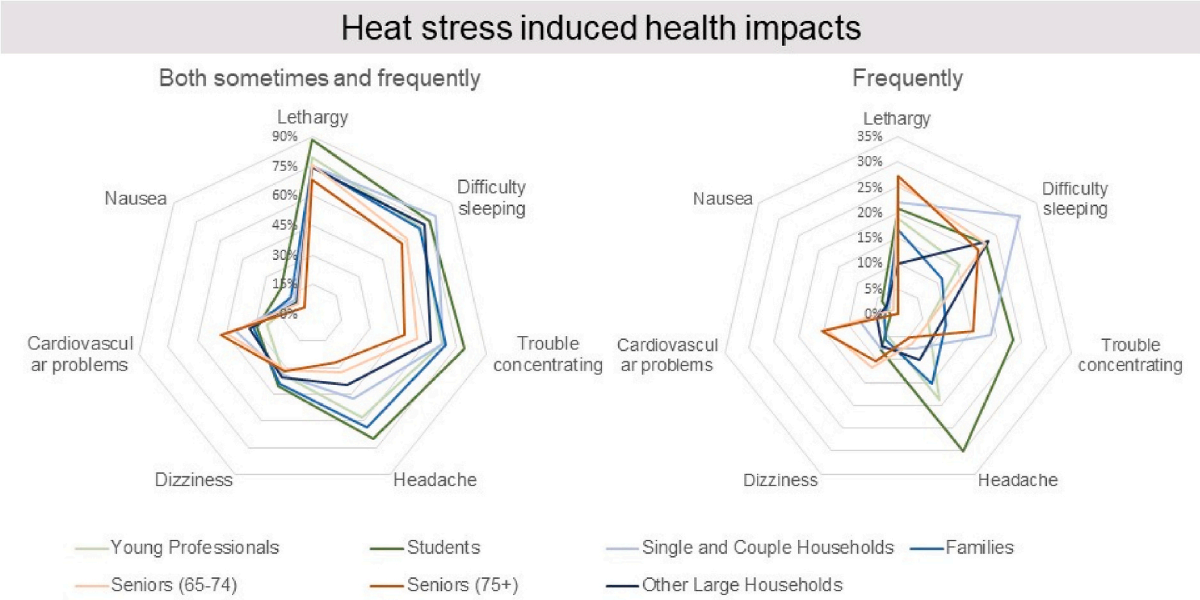

Fig. 3. Share of respondents in socioeconomic groups reporting heat stress induced health impacts.

groups. Likelihood of cardiovascular problems increased with age of survey respondents, with 29.5% of those over 64 experiencing such problems frequently. Almost one-third of Single and Couple Households were frequently impacted by difficulty sleeping while one-third of Students frequently had headaches or trouble concentrating. In comparison with the other socioeconomic groups, Families and Other Large Households were less affected by any of the health issues, though over 90% of respondents in both groups reported experiencing problems sometimes or frequently. This is an important finding to consider, since respondents' choice of frequently over sometimes likely indicates that impacts were experienced over a longer timeframe, and may have a higher impact on productivity, long-term health and quality of life.

4.2. *Exposure*

4.2.1. *Perceptions of heat in Bonn*

Overall, respondents reported high levels of perceived heat on public transport, with almost three-quarters of respondents (72.2%) indicating high or very high heat stress on the city's buses, subways and trams (Fig. 4). Areas around the city centre were considered another hotspot, with over two-thirds (68.7%) of respondents perceiving high or very high heat there. In contrast, when asked about

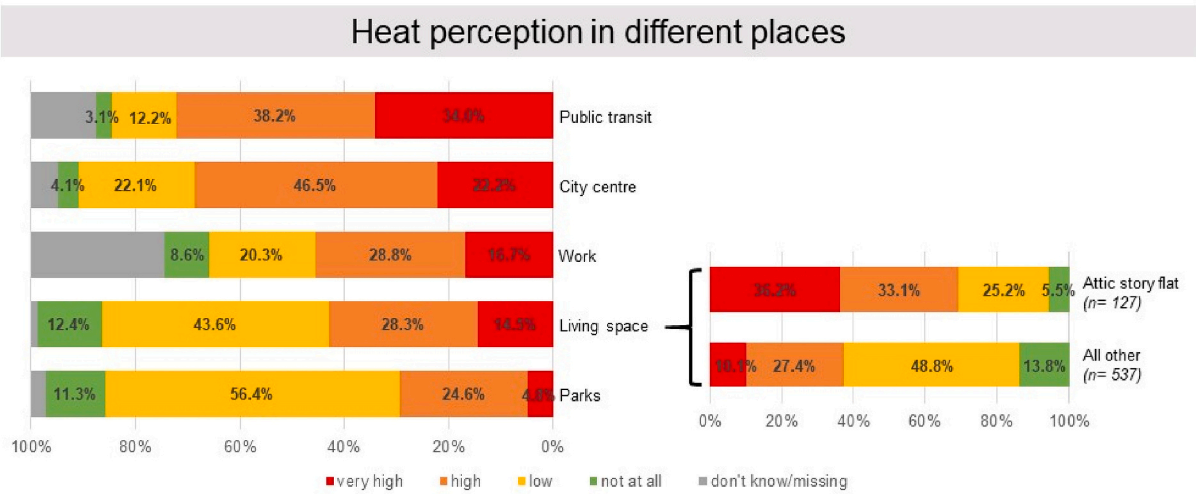

Fig. 4. Reported perceived heat in different places in Bonn and across different socioeconomic groups.

parks and public green spaces, a similar share (67.7%) reported that they never or rarely perceived heat in those areas, indicating that these places can provide refuge from heat stress.

The average heat perception in respondents' home environment is comparatively low, yet there is significant variation across different types of living spaces. Over two-thirds (69.3%) of surveyed households living in attic stories indicated high or very high heat stress, while almost two-thirds (62.6%) of households living in other types of apartments or houses reported experiencing no or only low levels of heat stress at home.

Following these results, living or spending time in the identified high heat stress areas was considered an indicator of heat exposure in the subsequent analysis.

4.2.2. *Exposure by socioeconomic group*

A notable gap in relative level of exposure is evident across the oldest and youngest socioeconomic groups for indicators related both to being present at heat hotspots (see 4.2.1) (EXP 1–2) as well as to living situation and behaviour (EXP 3–5) (Fig. 5). Seniors 64–75 and 75+ were characterized by low exposure (very low to low relative categories), while Students and Young Professionals were highly exposed (very high and some moderate to high categories). Overall, responses for the three groups in the middle age bracket (Single and Couple Households, Families and Other Large Households) fell in the moderate range for most indicators.

Interestingly, Seniors 64–75 and to a greater extent Seniors 75+ indicated comparatively low levels of exposure (Fig. 5). Seniors 75+ were the least likely to live in attic stories (EXP 1) and the most likely to have access to green space at home (EXP 3) and to have installed cooling features in their place of residence (EXP 4). Seniors 65–74 and 75+ reported adapting their behaviour to heat, and were less reliant than most other groups on public transit, with less than half (42.4%) reporting frequent use (EXP 2). Therefore, seniors were generally less likely than other groups to be exposed to heat stress in their home environments, as well as through their behaviour. This comparatively lower exposure should not be confused with their level of vulnerability.

Students (and Young Professionals, but to a lesser extent) were the most likely to report relatively high exposure for indicators related to the home environment. Out of all socioeconomic groups, Students were the most likely to live in attic story apartments (EXP 1) and to live in spaces that lack green space (EXP 3) and other cooling features (EXP 4). Though the results for Young Professionals were more mixed, people in this group still had moderate to high exposure for all indicators relating to living conditions. However, the share of respondents in these groups living in attic stories was relatively low, as evident by the smaller size of the bubbles for this indicator in Fig. 5. Only about one-quarter (24.7%) of Students, the most relatively exposed group for this indicator, reported living in an attic story apartment. Despite the low percent of affirmative responses, living in attic stories remains a dimension of high concern due to the high levels of heat stress reported by those who live there (see 4.2.1).

Furthermore, Students and Young Professionals were frequent users of public transit (EXP 2); this is the indicator with the largest gap in exposure across groups. For Students and Young Professionals, around three-quarters of both groups (76.6% and 71.9% respectively) used public transportation frequently. In the next most exposed group in this dimension, Single and Couple Households, only half (50.2%) reported frequent use. This indicates that it is primarily Students and Young Professionals who rely heavily on public

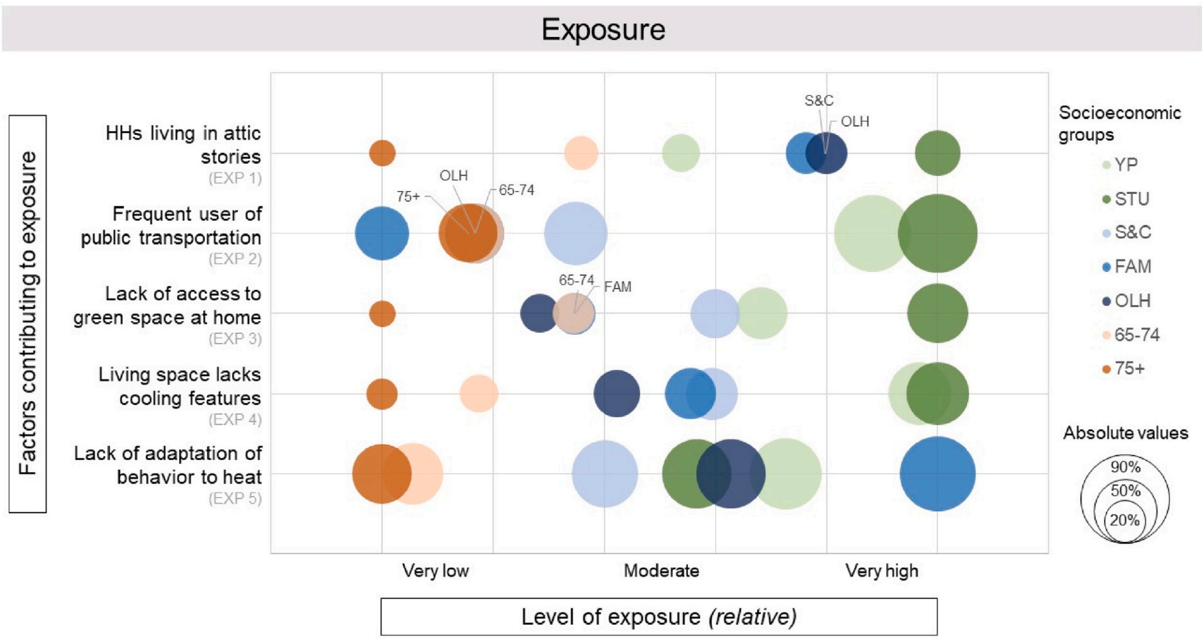

Fig. 5. Exposure across socioeconomic groups (abbreviations and colour schemes as introduced in Fig. 2). Absolute values (%) represented through size of the bubbles, while relative normalized values are portrayed through the position of the bubbles on the x-axis.

transportation, where they are more likely to experience heat stress.

Responses for Single or Couple Households, Families and Other Large Households fell in the moderate range for most indicators. For Families, however, relative exposure related to lack of adoption of heat-adapted behaviour (EXP 5) is concerningly high. Furthermore, Single and Couple Households and Other Large Households reported high exposure resulting from living in attic stories (EXP 1), which applies to 21.4% of both groups.

4.3. Vulnerability

4.3.1. Susceptibility

The two senior groups and Families were the only socioeconomic groups with very high levels of relative susceptibility, and are thus groups of high concern (Fig. 6) This was however expected, as two of the susceptibility indicators (young children and respondent age; SUS 2–3) were used to assign respondents to the socioeconomic groups, leading to very high absolute values for these groups.

The smallest differences in relative susceptibility between socioeconomic groups occurs for the indicator on household members with chronic illness and in need of care (SUS 1). This contributor to susceptibility was not confined to respondents in the two senior groups. While half (50.8%) of Seniors 75+ and about one-third (36.4%) of Seniors 64–75 indicated that at least one member of their household was in need of care, 26.4% of Single and Couple Households and 21.4% of Other Large Households also included such an individual. These results indicate that though susceptibility is concentrated with Families and the two senior groups, it is not uncommon for other households (especially those in the middle age bracket) to have increased susceptibility.

4.3.2. Coping capacity

Results for lack of coping capacity, displayed in Fig. 7, indicate a smaller gap across socioeconomic groups in comparison to exposure and susceptibility. Students have a high relative lack of coping capacity for indicators relating to characteristics of the living space (COP 1–2) and recency of move to Bonn or current residence (COP 3). Conversely, Seniors 75+ indicate relatively low lack of coping capacity for these three indicators. Coping capacity results varied considerably for socioeconomic groups in the middle age bracket. Across socioeconomic groups in Bonn generally, reported dependency on external support was high: on average, 77.3% of those surveyed responded that they would rely on civil protection or city authorities during a heat wave, contributing to significantly heightened vulnerability across socioeconomic groups (COP 5).

Seniors 65–74 and 75+ have a moderate to very high coping capacity for indicators related to living space. This indicates that these two socioeconomic groups generally have sufficient access to important coping mechanisms: cooling of living spaces and movement to cooler outdoor spaces, such as parks, during hot periods. It should be noted, however, that the high percentage of households in the senior groups that indicated an individual in the household needed care or was living with chronic illness (36.4% for Seniors 64–75 and 50.8% for Seniors 75+) may reduce accessibility of even nearby parks as a coping mechanism. Despite increased dependency on external support (COP 5), both Seniors 75+ and 64–75 are likely to have social contacts they can draw on for assistance, which increases their coping capacity.

In contrast, Students and Young Professionals have a high lack of coping capacity due to features of their living spaces, but fall more in the moderate range for social cohesion and dependency. Additionally, they have a high to very high lack of coping capacity when they recently moved to Bonn or when their current neighbourhood (COP 3) is considered. However, despite possible lack of social cohesion, connection to networks, and low familiarity with local resources associated with relative new arrival to a city or

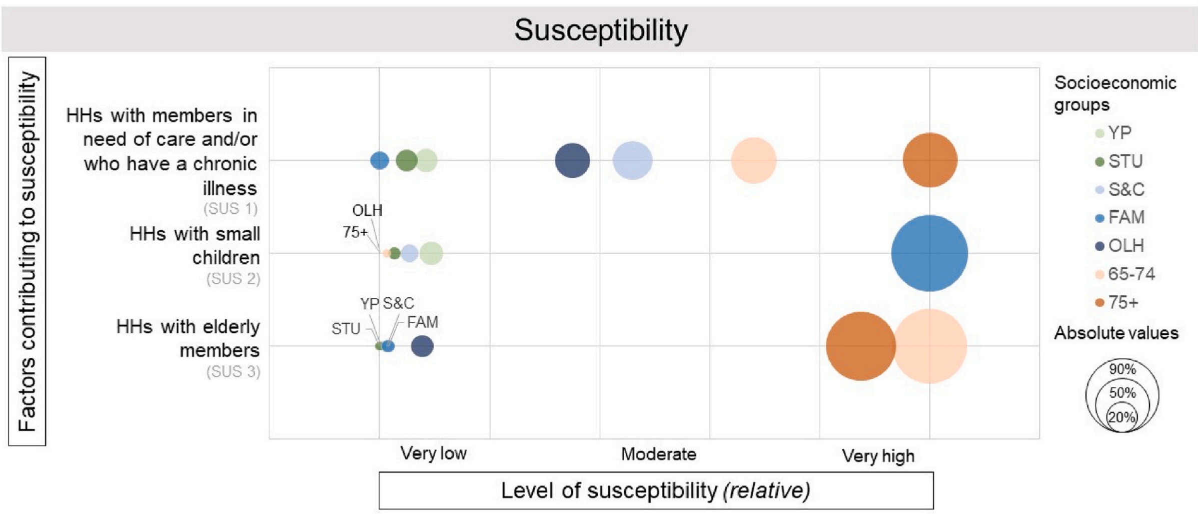

Fig. 6. Susceptibility across socioeconomic groups. Absolute values (%) represented through size of the bubbles, while relative normalized values are portrayed through the position of the bubbles on the x-axis.

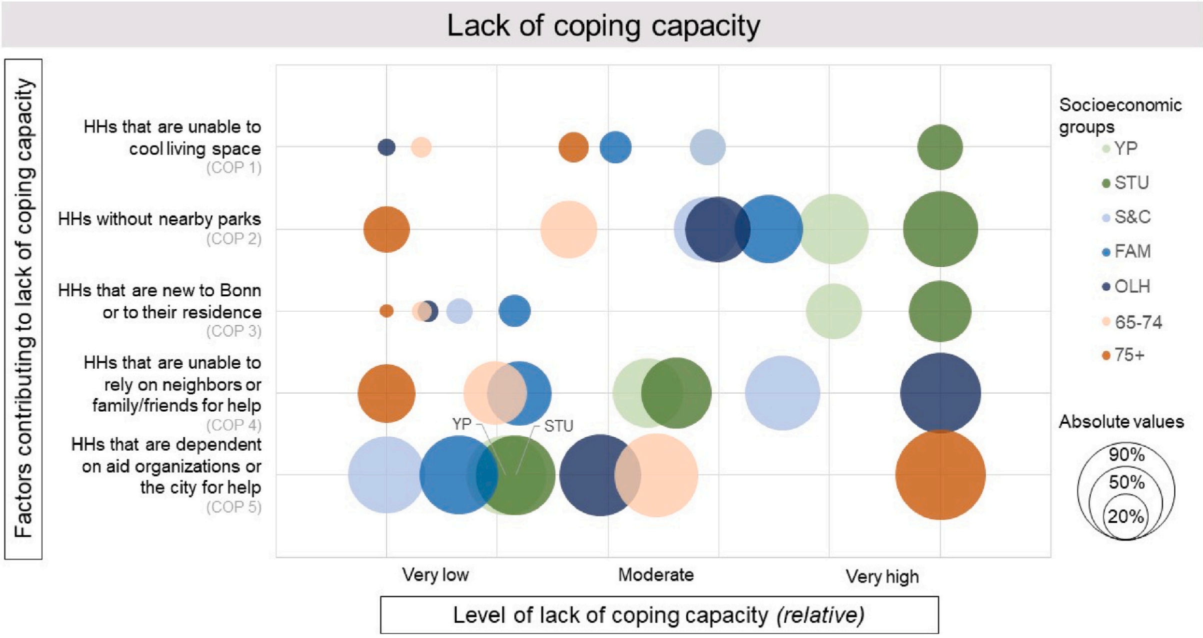

Fig. 7. Lack of coping capacity across socioeconomic groups. Absolute values (%) represented through size of the bubbles, while relative normalized values are portrayed through the position of the bubbles on the x-axis.

neighbourhood, Students and Young Professionals still indicated higher reliance on personal contacts and lower dependency on external support than older groups.

Other Large Households and Single and Couple Households have a high to very high lack of coping capacity stemming from a lack of reliance on social contacts (COP 4). As this is also coupled with high reported dependency on external support (COP 5), it contributes to an increased level of vulnerability in these groups. This is despite the fact that the Single and Couple Households group is the best performing group in the dependency dimension, represented by a comparably high coping capacity. Still, almost three-quarters (73.6%) of Single and Couple Households indicated reliance on external support.

4.3.3. Adaptive capacity

Results on adaptive capacity are quite mixed; no single group has a very high overall lack of adaptive capacity nor a very low overall lack, as displayed in Fig. 8. However, Students and Seniors 75+ are the only socioeconomic groups to have very high lack of adaptive capacity for any of the indicators. There is a clear distinction of results for indicators that consider a household's propensity to adapt (ADP 1–2) versus their ability to implement adaptation measures (ADP 3–5). In general, seniors tended to have an increased lack of adaptive capacity due to low propensity to adapt while younger socioeconomic groups lacked adaptive capacity due to low feasibility of implementing adaptation measures.

Seniors 75+ have the lowest risk awareness (ADP 1) and intention to adapt (ADP 2), resulting in the highest relative lack of adaptive capacity in these two dimensions. Seniors 64–75 diverge from the older cohort on risk awareness (ADP 1), with 16.9% of these respondents not viewing heat as a future threat compared to 33.9% of those over 75. However, the absolute values of the risk awareness indicator are quite low, as the majority of households in all socioeconomic groups (73.4%) did consider heat to be a future threat. In the dimension of adaptation planning (ADP 2), the two senior groups are very similar, with relative lack of adaptive capacity in the high to very high categories.

Despite very high adaptive capacity among both senior groups for indicators related to adaptation feasibility, it is important to note those 75+ were generally less willing to invest private money in adaptation, with very high relative lack of adaptive capacity in this dimension (ADP 5). In comparison, 42.9% of Seniors 64–75 were unwilling to invest in adaptation (putting them in the very low category), compared to 57.6% of those over 75.

Students show the highest relative lack of adaptive capacity for all three indicators related to means to implement adaptation measures. The discrepancy with other groups was largest for low income (ADP 4), which applied to all Students and thus far exceeded the overall average of the complete sample (22.7%). However, such a gap was expected, as low income was one criteria for respondents to be classified as Students. Young Professionals were similarly likely to be renters but did indicate moderate willingness to invest in adaptation measures (ADP 5), with 50% being willing.

In the middle age bracket, Single and Couple Households show an increased level of vulnerability due to moderate to high lack of adaptive capacity for four out of the five indicators. In contrast, Families and Other Large Households had a comparatively high adaptive capacity, which reduces their vulnerability. Families show high to very high adaptive capacities for all indicators except for rental status (ADP 3), which is high. For Other Large Households, the only indicator contributing to increased lack of adaptive capacity

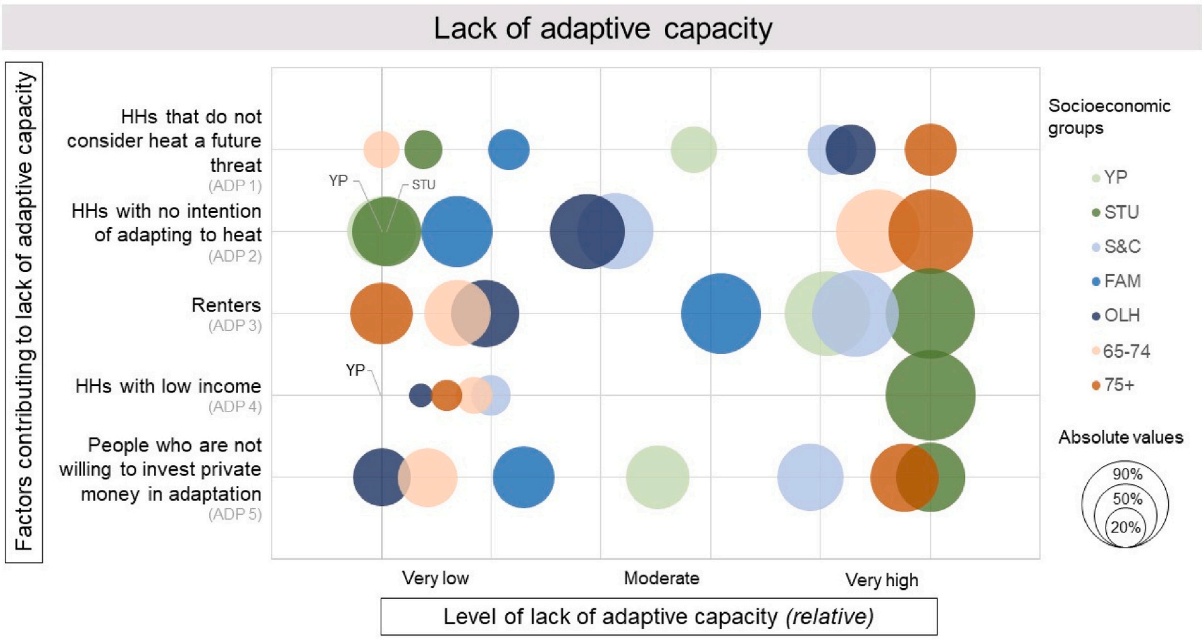

Fig. 8. Lack of adaptive capacity across socioeconomic groups. Absolute values (%) represented through size of the bubbles, while relative normalized values are portrayed through the position of the bubbles on the x-axis.

is low relative risk awareness (ADP 1).

5. Discussion of overall exposure and vulnerability

Results indicate that all socioeconomic groups are at risk of urban heat stress, though to differing extents and for different reasons. Therefore, this work goes beyond the existing body of literature, which still very much focuses either on selected societal groups like elderly (Arnberger et al., 2017) or on risk components (Ogato et al., 2017), instead of more holistic assessments (Hoehne et al., 2018). The study demonstrates the need to take a deeper look at the different risk components, as they vary greatly across groups. Exposure was lowest in older age groups which are usually considered to be at highest risk from urban heat. Their relatively lower exposure was the result of comparably better housing conditions and a high potential to adapt their behaviour to heat, as they are usually retired or no longer part of the working population with its potentially fixed working hours. At the same time, and as expected, the age groups above 65 were most susceptible, with those above 75 having the highest susceptibility; coping and adaptive capacities were also comparably high. However, a few factors stand out that limit capacities. There is a sizable lack of adaptive capacity for the two indicators of adaptation propensity, perhaps due to these groups regarding adaptation as the responsibility of younger generations. Respondents in the Seniors 75+ group might be unwilling to invest in adaptation measures as benefits may not become evident during their lifetimes.

On the other hand, Students and Young Professionals are almost opposite of older age groups for most risk components. They face comparably high exposure and lack of coping capacity, likely due to their living conditions as more mobile groups with rented and comparatively poorly adapted apartments and with fewer green areas nearby. Rental status and comparably low financial means to implement adaptation measures limit their comparably high intention to adapt. Students in particular are more likely to be on low or fixed incomes, contributing to their lower capability despite high willingness to self-fund adaptation measures. Part of their high exposure is due to high usage of public transportation, a location that respondents considered very uncomfortable during hot periods. As a result, Students and Young Professionals are more exposed due to their climate-friendly behavioural practices. However, these groups are not necessarily on the radar of urban decision-makers. Existing governance strategies rather focus on other societal groups (Donner et al., 2015; Mahlkow and Donner, 2017), raising critical questions on their potential for guiding overall urban development and risk reduction strategies.

The same is true for most middle-aged households, with the exception of Families with young children which are, along with the elderly, usually considered a high-risk group in the literature. However, besides slightly higher susceptibility, overall risk is at a comparable level across Single and Couple Households, Families and Other Large Households. Exposure as well as lack of coping and adaptive capacities are all at moderate levels, ranging between younger and older groups. Families state a low willingness to adapt their behaviour to heat, probably simply due to decreased scheduling flexibility for parents with young children, a factor which should be taken into consideration when examining heat exposure of this group. At the same time, they are ranked last in using public transportation, lowering their exposure.

Overall, each of the assessed socioeconomic groups has particular strengths and weaknesses when it comes to capacities. Though older socioeconomic groups have heightened susceptibility, their overall risk may be at least in part offset by coping and adaptive capacity which exceeds that indicated by younger respondents, who are more financially insecure and therefore forced into less favourable apartments. In contrast, younger respondents displayed high risk awareness, and indicated that they were more likely to alter their behaviour to adapt to a future environment in which heat waves are more of a problem. However, they might not be able to make necessary changes due to lower quality living conditions and lack of financial means, resulting in an adaptation gap in a time when rapid action is needed.

On a higher level, our results reveal that vulnerability and exposure are strongly linked and that, in general, lack of income and also to some extent a lack of local networks leads to higher exposure. Another key pattern is the comparably higher willingness of younger groups to adapt. Low willingness among older groups has the potential to stand in the way of more extensive adaptation efforts, since these groups are more likely to own their properties and to have resources to invest. This indicates that offering only financial incentives may not be enough; instead, likelihood of success needs to be bolstered by group-specific interventions. Here our study addresses a topic not yet dealt with, although previous literature has pointed at the gap (Wolf et al., 2015; Ellena et al., 2020), in both research and policy.

6. Conclusion

This study has shown how important it is to more precisely capture the patterns of urban heat risk across different socioeconomic groups, which so far have rarely been analysed in a systematic way. Urban residents who do not fall into "classic risk groups" are affected by heat stress in ways that may not be accounted for in current policy measures and community outreach strategies. Groups such as the elderly, which are at the core of both policy action and research, may not always have the highest level of risk.

Our review of the literature on heat risk assessments revealed that few studies take a granular approach to exposure and vulnerability (Voelkel et al., 2018), or consider individual experiences of heat stress (Zhang et al., 2018). The first main conclusion of this study is therefore that an analytical framework assessing risk through the lens of its components provides a much needed more nuanced picture of the different challenges socioeconomic groups face. Connecting heat stress risk indicators to individual components of risk allows for more precise identification of problem areas for specific groups, which can then be more readily tied to tailored solutions. In addition, an analytical framework as presented here can be a first step in clustering so-far heterogeneous indicators, thus improving the comparability of analyses.

Looking at the perceived impacts of heat stress across socioeconomic groups, our second main conclusion is that all groups reported serious impacts, including younger age groups, which surprisingly reported impacts at the highest rates. Although or precisely because reported health impacts are a matter of personal perception, these results should be taken seriously. Elderly people might not perceive heat as a problem because they suffer other health issues that to them are more important and troublesome, but which might be exacerbated by heat in future. These differing effects stem from intricate compositions of risk, e.g. younger people who are expected to be in comparably better health, but who have high exposure and low coping capacity, or older groups who have a very high susceptibility but who—despite comparably good overall coping capacities—are less willing to adapt. These findings add further weight to our first conclusion, namely that risk must be viewed through the lens of its components, which are best captured by fine-grained approaches. Moreover, this study showed that all health aspects should be considered, including heat stress induced impacts on mental wellbeing. People having difficulty sleeping or trouble concentrating might suffer from serious long-term effects, which need to be considered in adaptation planning. The study thereby advances existing studies focusing on mortality or more immediate health impacts, particularly on the elderly (Akerlof et al., 2015; Arnberger et al., 2017; O'Lenick et al., 2019), by pointing at accumulating long-term risks on all age groups.

Based on these conclusions, a key takeaway of this study is the importance of looking at all urban inhabitants instead of focusing on a few groups exclusively. It is necessary to take a detailed look at risk patterns, adaptive capacities and attitudes towards adaptation across socioeconomic groups .For example, both Students and Seniors 75+ reported not being willing to invest their own money in adaptation, however the reasons for this may differ. For Students, the reason may be reported low income, while those over 75 did not consider heat a future threat. There was no socioeconomic group with an overall low risk profile. In general, older groups were more susceptible but had comparatively higher coping capacities while younger groups in particular showed the opposite pattern. Overall, this does not downplay risk faced by older age groups, but highlights two important points: groups apart from elderly and young children can also be at risk, and each group has its own capacities with the potential to mitigate risk. These findings are particularly relevant to inform the development of targeted and context-specific policies, as e.g. claimed by Weber et al. (2015), Lapola et al. (2019) and Zemtsov et al. (2020).

Finally, this study showcases that there are no easy fixes to address the broad, complex challenges involved in adapting cities to future heat. Cities need to link climate adaptation strategies, including measures to mitigate heat, to other urban challenges and risks. The high exposure reported in public transportation should raise questions about its quality, which potentially hinders the shift towards more sustainable urban transportation systems. Traditional cooling strategies that a city might recommend, such as use of heat shelters or seeking refuge in shared public spaces, are for instance no longer an option in times of social distancing during pandemics. City planning thus needs to link sectors to jointly develop holistic and systemic risk management strategies.

Similarities in building stocks or urban layout do not equal transferability of adaptation measures to other quarters or cities. When formulating adaptation measures, it is necessary to take a detailed look at socioeconomic groups and their risk patterns, thereby advancing targeting (see e.g. Verdonck et al., 2018). In the case of Bonn, it is important to also consider how Students and Young Professionals are affected by heat; in other cities, different socioeconomic groups may be of greater relevance. Therefore, assessments

like the one presented here can play a key role in informing urban planning by enabling tailoring of specific adaptation measures. The results can therefore be understood as a call for urban authorities to critically review current programmes and initiatives to reduce heat stress. Standard policy interventions such as tax incentives or cost absorption for house owners may fail to reduce overall risk because they either do not target the right groups, cannot be used by those who would be willing to adapt, or simply because those who could implement measures do not see the need. To support cities, more capacities but also tools to assess risk in a holistic way are necessary to better tailor interventions, but to date they are scarce.

Physical interventions by improving housing conditions and urban patterns would be a core element in any plan to reduce exposure and related negative impacts on health. This would particularly benefit "non-classic" risk groups who reported serious—though mostly non-life threatening—health effects. Such measures might also positively impact general well-being and reduce negative consequences from other shocks, such as the ongoing COVID-19 pandemic. However, long-term risk reduction portfolios will need to look beyond concrete interventions by including non-structural measures to improve coping and adaptive capacities.

To adapt cities to heat, it is not enough to know which parts of a city are getting hotter; policy-makers and urban planners need to know and consider which groups are most likely to experience heat stress, the underlying causal factors, and what the individual scope for action is.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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