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Threshold temperatures for subjective heat stress in urban apartments—Analysing nocturnal bedroom temperatures during a heat wave in Germany

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ABSTRACT

As climate change progresses, it is causing more frequent and severe heat waves, resulting in higher indoor temperatures. Various temperature thresholds for indicating indoor overheating have been proposed in different contexts, extending from reduced comfort in buildings to subjective heat stress and onset of first or serious health problems. This study reviews these thresholds and identifies threshold values for subjective heat stress of occupants in the city of Augsburg, Germany, distinguishing between vulnerable and non-vulnerable households. Survey data from 427 private households are analysed using unpaired analysis of variances (ANOVA), *t*-tests and regression analysis to identify factors related to subjective heat stress at home during night-time. The findings imply that health implications during heat waves, age, local climate zones favouring the urban heat island effect and higher indoor temperature represent significant factors for subjective heat stress. A significant difference in subjective heat stress among different groups related to temperature could be identified for thresholds of 24.8 °C (people living alone) and 26.7 °C (people with chronic disease). As WHO threshold for health risk from overheating is 24 °C, people are apparently at heat-related risk without feeling that they are at risk, especially when they have chronic diseases; thus they may not see the urgency of taking adaptation measures.

1. Introduction

Rising temperatures and an increasing number of hot days are expected consequences of climate change (IPCC, 2019; Cowan et al., 2020). By the end of this century, exposure to heat waves will be four to eight times higher (as measured by frequency, duration and extreme temperatures) than at the beginning of the century (Wang et al., 2020). Another factor affecting both the severity and frequency of heat waves and the number of people exposed to them is urbanisation (Luo and Lau, 2017). It is estimated that by 2050, around 70% of the world's population will be living in cities (United Nations, Department of Economic and Social Affairs, Population Division, 2019), which are more strongly affected by heat waves. A major reason is the urban heat islands (UHI) effect, which is subject to various studies and is directly linked to the size of the urban area. The effect is caused by absorbent materials of the built environment capturing solar radiation in the form of heated materials during the day and releasing the heat slowly over night (Luo and Lau,

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2019a, Lauriola, 2016), it is leading to a larger number of exceptionally warm days and nights (e.g. tropical nights: nights with minimum air temperatures ≥ 20 °C), contributing to severe heat stress that affects human physical and mental health (Lei Zhao et al., 2014). Physical symptoms, such as excessive thirst, sweating, dizziness, nausea and headaches lead to mild to severe health-related illnesses e. g., heat stroke, heat exhaustion, and even death (Kilbourne, 1997; Kovats and Hajat, 2008). Various studies have investigated excess mortality linked to heat waves which can be determined by a peak in the number of deaths during extreme temperatures (e.g. Kovats and Hajat, 2008). Similar peaks can be found for different extreme events, such as hurricanes (Spagat and van Weezel, 2020) and flooding (Yan et al., 2020). In terms of mental health, latest studies show that heat stress reduces people's well-being and life satisfaction, resulting in low energy levels and emotional problems (Arifwidodo and Chandrasiri, 2020). In India, Koteswara Rao et al. (2020) project an up to 40% decrease in work performance caused by rising heat stress levels until the end of the century. Moreover, evidence shows that, in regions with moderate summer temperatures, heat-induced health impacts may be large, likely because people are less experienced with heat and do not have the time to acclimatise, such that the mortality rate already rises at lower temperature thresholds, this makes Europe a sensitive region (Gosling et al., 2009; Medina-Ramón and Schwartz, 2007). The rising mean age of Europe's population is another factor in heat waves causing not only severe health impacts but also high mortality rates (Ballester et al., 2011). In the summer of 2018, there were>104 000 heat-related deaths among people over 65 years in Europe; in Germany alone, there were around 20 200. For comparison, there were 19 000 in the United States, where air conditioning is a substantial factor decreasing heat-related deaths (Bouchama et al., 2007); notably, most German homes are free-running.

The symptoms of a heat-related illness leading to death are often insidious, and for many people, not recognisable, e.g. dehydration, excessive sweating and its consequences, this makes heat waves a 'silent killer' compared with other natural disasters like flooding or storms (Mishra and Suar, 2007). To overcome these health threats, it is important to develop adaptation strategies for private households (Hondula et al., 2015). Next to duration, one of the main factors responsible for heat wave health impacts is the night-time temperature (Fischer and Schär, 2010) because reduced sleep quality under heat stress is another key issue that negatively affects people's mental capacities and threatens psychological and physical health (Wong et al., 2018; Okamoto-Mizuno and Mizuno, 2012). However, if citizens and society do not perceive heat waves as a risk or feel heat stressed, they do not see the need to adapt, making subjective heat stress crucial for taking measures against overheating.

To better understand heat perception, subjective heat stress and its determinants have been analysed in several cities (Borchers et al., 2019; Franck et al., 2013; Großmann et al., 2012; Kunz-Plapp et al., 2016; Seebass, 2017). However, there is no insight yet about temperature thresholds for subjective heat stress as an orientation in German cities. In a comparison with the results of studies on subjective heat stress, this study uses the indoor temperature of private households to assess temperature thresholds for reported heat stress at night. After an overview of mean nocturnal temperatures in different study households, the following research questions are addressed: Which factors are related to subjective heat stress of occupants in the city of Augsburg at night? At which night-time indoor temperatures do people start feeling heat stressed?

Knowing the factors influencing subjective heat stress and temperature threshold (ranges) for subjective heat stress would allow heat risks to be managed in urban areas with similar climatic conditions more effectively and efficiently. For example, exposed occupants in the research area could be informed about heat stress and adaptation measures. Existing knowledge about outdoor temperature thresholds for excessive death (e. g., Mora et al., 2017) could be used as indicators of relevant outdoor temperature and humidity. Because the buildings in this study are free running, where the indoor temperature varies in each apartment individually, it is not sufficient to focus on outdoor temperature and humidity. Therefore, the results in this study give explicit *indoor* temperature thresholds for different target groups when they start feeling heat stressed. Those thresholds can easily be included in municipal heat action plans, as well as in private community groups taking care of each other, as thresholds for acting, such as by starting a control round in effected households. They also give guidance on when certain groups should be contacted and reminded to take adaptation measures because they do not (yet) feel the need to do so. Further implications could arise for building codes and occupant rights regarding rent reduction, as feeling heat stress is definitely a sign of a reduced comfort level. The findings are applicable managing heat risks in several institutions, including hospitals, retirement homes and home care nursery services. They will also be helpful for private heat management, indicating the need for individual adaptation measures especially among vulnerable groups In the future, this information will be even more valuable when sensors in households might be connected in smart cities and communicate indoor temperature autonomously.

This study is based on temperature and survey data of 427 households that were collected in the city of Augsburg, Germany, 70 km NW of Munich, from 427 households during the summer months of 2019. The remainder of the paper is structured as follows: After a literature overview of heat stress. subjective heat stress and overheating thresholds in section 2, section 3 outlines materials and methods. Reported subjective heat stress and night-time indoor temperatures of apartments in Augsburg during the 2019 heat wave are analysed in section 4 followed by the discussion in section 5 and the conclusion in section 6.

2. Background

To better understand overheating thresholds and to compare them with thresholds for subjective heat stress, this section first provides information about subjective heat stress and its consequences. It then summarises temperature thresholds in standards and other sources from various countries that are used as indicator values for overheating.

2.1. Thermal comfort and heat stress

The measurement of heat affecting individuals before increased mortality occurs is often conducted via indices of thermal (dis) comfort. *Thermal Comfort* is defined as a persons' mental satisfaction with the thermal environment (Epstein and Moran, 2006). According to Fanger (1970) six factors influence a persons' thermal comfort, including the wet and dry bulb temperatures; black-globe temperature; wind velocity; metabolic rate; and clothing, insulation and moisture permeability. This author developed the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) models. Moreover, developing a model predicting risks for overheating of a building, Robinson and Haldi (2008) included a person's subjective feeling on overheating, and adaptation options. They pointed out that some newer standards and studies include comfort temperature of occupants (de Dear and Brager, 2002; Humphreys, 1978; Nicol and Humphreys, 2002); they have started to define 'comfort envelopes' for free-running buildings. Indeed, the PMV and PPD, as well as the adaptive model by de Dear and Brager (2002), are often used to assess occupants' thermal comfort. However, Hughes and Natarajan (2019) show that these parameters cannot determine the thermal comfort of elderly people during an extreme hot summer, and according to the Chartered Institution of Building Services (CIBSE), 94% of bedrooms were overheated in the summer of 2018.

Although, the literature on thresholds shows that there are differences between living room and bed room temperature thresholds (section 2.3), Fanger et al. (1974) claimed that a person's thermal comfort level is not the same during day and night because of the slower metabolism at night-time. However, Di Nisi et al. (1989) showed that, during the second night of sleeping in hot environment, sleep quality is already poor, with subjects sleeping restlessly and less efficiently. This underlines the need to focus on night-time temperatures during heat waves.

A persons's satisfaction can be disturbed by heat stress. To assess heat stress, it is necessary to apply an index, many indices can be found in the literature (see, Epstein and Moran, 2006, for an overview of 25 different indices measuring heat stress). Different scales are used, for example, the psychological effective temperature (PET) or the universal thermal climatic index (UTCI) equivalent temperature, which divides the dry bulb temperature into different stress levels reaching from extreme cold stress (below − 40 °C) to extreme heat stress (above 46 °C; Błażejczyk et al., 2010).

In conclusion, heat stress is caused by the human body's exposure to various factors, such as, excessive temperatures (depending on the chosen index), leading to serious heat illness. The body's reaction to heat stress is heat strain, which may be expressed via excessive sweating and other health implications, such as nausea, cardiovascular problems and heat cramps (Belding and Hatch, 1955; Jendritzky and Tinz, 2009). Factors associated with heat stress include young age, poor health status and chronic diseases, type of housing (buildings with many apartment units), no air conditioning and less adaptation measures taken (Kovats and Hajat, 2008). Luo and Lau (2019b) found that heat stress in China, for example, is caused by high temperature rather than humidity, making temperature a crucial factor.

2.2. *Subjective heat stress*

Besides the real heat stress that can be determined, the person's *subjective perception* of heat stress plays an important role. In their study, Wang et al. (2017) showed that real temperatures and thermal conditions are not as important for a person's perceived comfort as other subjective factors (e.g., natural view or emotional background). Thus, research needs to consider these subjective factors in relation to indoor temperatures to better understand relations and give recommendations for action plans. Earlier studies investigated factors influencing the perceived heat stress in private households (Borchers et al., 2019; Franck et al., 2013; Kunz-Plapp et al., 2016; Großmann et al., 2012; Seebass, 2017). Results are described in the following.

Socioeconomic factors that significantly influence subjective heat stress include the individual health status or health impairment, higher age, a lack of social interaction, feeling helpless against heat; less adaptation measures taken and being female (Borchers et al., 2019; Kunz-Plapp et al., 2016; Seebass, 2017). Building characteristics associated with higher subjective heat stress are as follows: living on higher floors; in rented apartments; in older houses; far away from green areas or in areas with high building density; the lack of a possibility to sit outside; lack of thermal insulation; higher heat load of the district; houses with more apartment units and higher bedroom temperature in the evening (Borchers et al., 2019; Franck et al., 2013; Großmann et al., 2012; Kunz-Plapp et al., 2016; Seebass, 2017). Table 1 gives an overview of the identified significant indicators for subjective heat stress in the literature; these are included in the correlation analysis to identify factors influencing subjective heat stress. Note that a factor measuring the speed of temperature increase in the bedroom was added as determined from linear regression of night-time temperature evolution over three hot days during a heat wave in Augsburg. The rationale behind this is that the human body is less affected if there is more time to adapt

Table 1
Overview of significant indicators for subjective heat stress.

Significant socioeconomic factors	Significant building- and temperature-related factors
Poor individual health status/ many health implications	Living on higher floors
Older age	Living in older building
Lack of social interaction	No possibility to sit outside
Feeling helpless against heat	No thermal insulation
Being female	Local Climate Zone (less green, higher building density)
Greater number of people living in household	Type of housing
Lower education	Living in a rented apartment
Unemployment	High slope of regression of night-time indoor temperature during heat wave period
Lower income	Higher temperature of bedroom during night-time
Lower number of adaptation measures	

to higher temperatures.

Seebass' (2017) study did not show significant effects for the factors of living alone, lower income, lower education and being unemployed. In addition, the urban structure type and whether there was greenery around the house could not be confirmed as influencing subjective heat stress (Franck et al., 2013; Seebass, 2017). Franck et al. (2013) reported no significant effect of outdoor temperatures, whereas Kunz-Plapp et al. (2016) reported no effect of age or gender on subjective heat stress. Few studies have considered real temperature data in their analyses. Some studies have analysed temperature thresholds for thermal comfort supporting quality of sleep (Ohnaka and Takeshita, 2005), but there has not yet been an analysis of a nocturnal temperature threshold during heat waves for quantifying subjective heat stress. However, such temperature thresholds are important for risk management action plans during heat waves, both for crisis management and preventive measures.

2.3. Thresholds of apartment overheating

Overheating of apartments and commercial buildings and its consequences have been widely researched in the literature (e.g. Lin et al., 2019; Mavrogianni et al., 2012; Sharifi et al., 2019). Lomas and Porritt (2017) reviewed eight publications on overheating in apartments from the United Kingdom. Below, temperature threshold values used in the literature or recommended by institutions to describe overheating (the threshold at which an apartment is considered to have negative effects on comfort and/or health) are presented for subsequent comparison with the threshold values determined in this study's analysis to answer the research question. This overview of existing thresholds from different countries illustrates how the overheating of an apartment – specifically, a bedroom – is subject to its location, with its climate conditions, and the standard that is applied.

A commonly used threshold in research is that recommended by CIBSE, which follows the British and European Standard BSNE15251 (British Standards Institute, 2006). The CIBSE guide suggests that temperature in bedrooms should not exceed 26 °C for>1% of the annual occupied hours because sleep quality drops for temperatures above 24 °C (CIBSE, 2015). This threshold has been used by various authors (e.g. Beizaee et al., 2013; Hacker et al., 2008), adopting an assumed occupancy of bedrooms from 23:00 to 7:00. However, there are often difficulties applying the 1% threshold because temperature data are not available for the whole year or the occupied hours cannot be determined with high accuracy. Therefore, the 1% threshold is sometimes calculated for the summer period only (Wright et al., 2005), or the occupancy time determined in interviews is supposed to be the same for various apartments (Baborska-Narożny et al., 2017). Another option is to use a static value of 26 °C as a threshold, neglecting the 1% admissible exceedances implied by CIBSE in the TM59 (CIBSE, 2017, e.g., Vellei et al., 2017), or to rely on thermal modelling of existing or future scenarios using Design Summer Years and Hot Summer Years offered by CIBSE (Liu and Coley, 2015). The National Health Service (NHS) sets the same threshold value of 26 °C for 'cool areas and rooms' in the Heatwave Plan for England (NHS England, 2015). For Germany, the standard contains threshold values in the form of acceptable excess temperature hours depending on the type of building usage (1200 Kh/a for residential buildings and 500 Kh/a for non-residential buildings) and the climate region (e.g. 25 °C for Climate Region A, 26 °C for Climate Region B and 27 °C for Climate Region C (depending on the interaction between air temperature and solar radiation; Region A: coast and mountain regions; Region C: mainly Rhine region and some tributary streams; Region B: remainder; DIN 4108-2:2013-02). Independently from this standard, in Hamburg a German district court decision from 2006 judged that a temperature of 25 °C should not be exceeded at night for bedrooms; otherwise, a rent reduction can be justified (Amtsgericht Hamburg, of 5/10/2006). It is worth mentioning that Hamburg belongs to Climate Region B. In contrast to the temperature thresholds mentioned above, the WHO argued that there is no notable health risk for people living in houses with indoor temperatures between 18 °C and 24 °C, and therefore, they use a threshold of 24 °C in their housing and health guidelines (WHO, 2018). After reviewing the literature on sleep quality and temperature, Peacock et al. (2010) decided to use 23.9 °C at 23:00 as the threshold value for bedrooms.

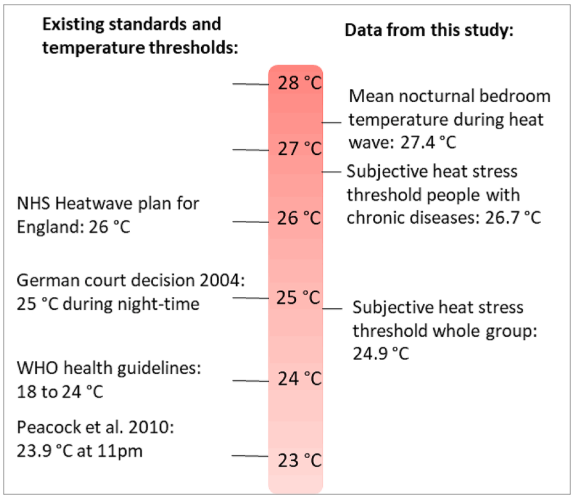

Fig. 1. Existing thresholds versus data from this study; own depiction.

As the literature overview shows, there are different temperature thresholds from different countries and climatic regions, used as indicators for overheating where overheating may result in reduced comfort and/or negative health impacts. When comparing such values, their origin and purpose need to be accounted for because it makes a difference whether a certain value qualifies as a reason for abatement of rent, represents the limit value at which sleep quality begins to drop, serves for building planning and so on. Further, threshold values alone (i.e. without admissible exceedances; details about measurements, including exact location and time; and further processing, such as averaging, sum of exceedances, etc.) are hardly comparable. In sum, threshold values in the literature range from 24 °C to 26 °C and are often linked to an admissible time of exceedances. However, during heat waves, these threshold values are often greatly exceeded (Hendel et al., 2017). Identified thresholds are summarised in Fig. 1.

3. Material and methods

This section describes the research design and data set of the study. Data were collected in the frame of the interdisciplinary project ‘Augsburg stays cool’ (Augsburg bleibt cool, 2020), funded by the German Federal Ministry for the Environment (BMU), in November 2018 to December 2020. The overall aim of the project was to identify urban thermal hot spots in the city of Augsburg, as well as raise awareness of heat risk among the citizens and develop heat adaptation measures for the community. To do this, bedroom temperatures in households were measured during the 2019 heat wave, as explained below.

3.1. Research design

Around 600 temperature data loggers were distributed to measure and log indoor temperature in bedrooms every 15 min from July to September 2019. According to the manufacturer, the employed loggers (Elitech RC-5) have an accuracy of ± 0.5 °C (Elitech, 2020).

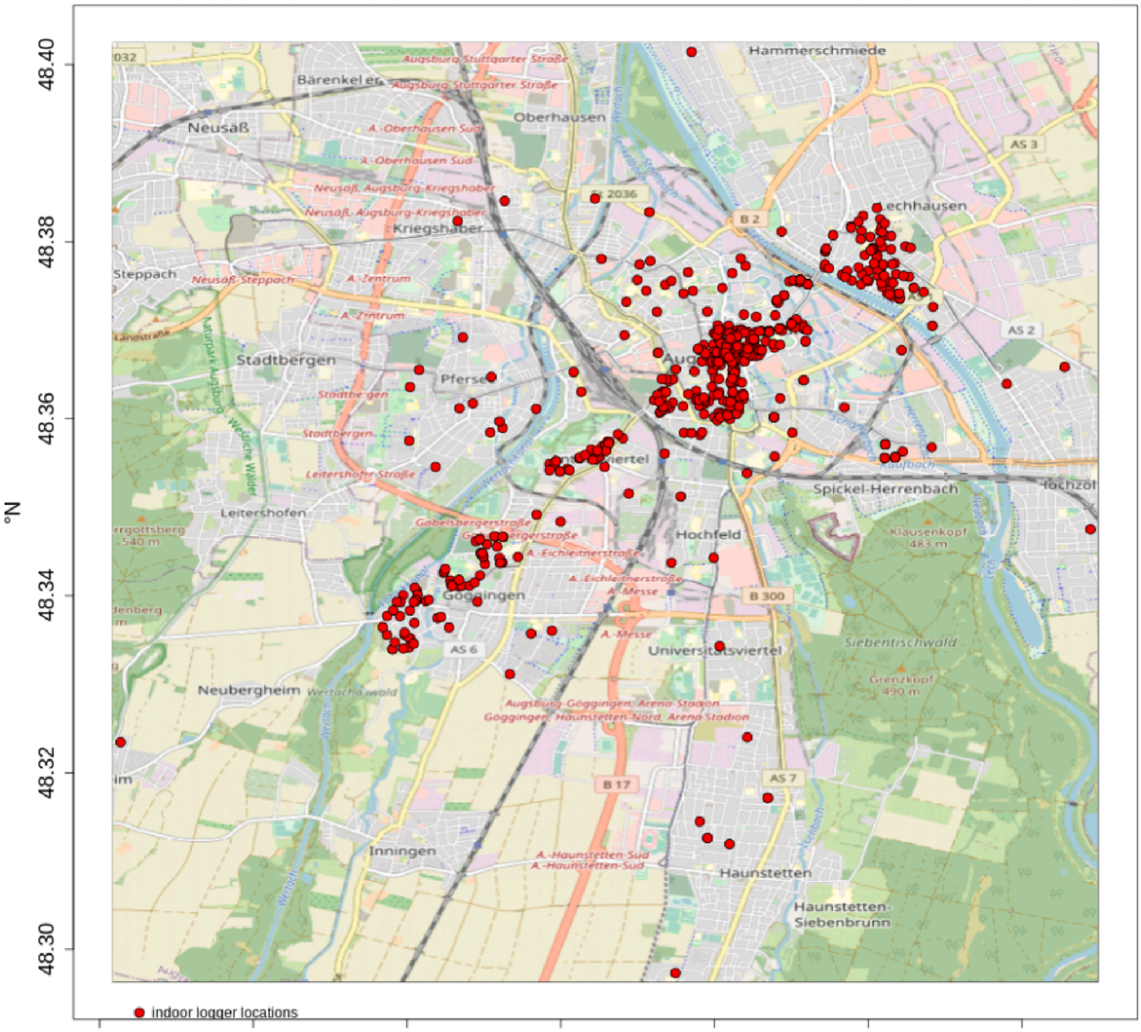

Fig. 2. Locations of indoor temperature loggers (red dots) in the city of Augsburg (Background map source: Open Street Map).

This specification was confirmed by exemplary calibration experiments performed for 10 randomly chosen loggers with a precision temperature generator. To ensure meaningful measurements, precise instructions concerning the positioning and maintenance of the loggers (especially, avoiding exposition to direct solar radiation or any artificial heat sources/sinks, no relocation during the duration of the study, documentation of any potentially perturbing incidents) have been provided to the participants of the study. The loggers were accompanied by a questionnaire, asking sociodemographic and building-related details, as well as questions regarding heat stress perception. The survey took place in July 2019 among participants who agreed to place a data logger in their bedrooms. In total, 468 surveys were completed. Outdoor temperature and humidity were recorded simultaneously by an already existing comprehensive urban climate-measuring network (Beck et al., 2018).

The participants of the study were selected following simple random sampling within the research area. The research area for bedroom temperature measures was defined focussing on Local Climate Zone (LCZ) categories (compact mid-rise, open mid-rise and open low rise), covering urban neighbourhoods with various building characteristics (e.g. age, type, height and density of the built environment). The underlying LCZ mapping for the Augsburg urban area was determined according to the workflow described by Bechtel et al. (2015) utilising several Landsat scenes from 2014/2015 (see Beck et al., 2018 for details of the LCZ classification). Four thousand households in the target area received invitation letters to participate in the study and were able to sign up to receive their data-loggers, the information sheet regarding the handling of the logger and their access to the survey; alternatively, they took part in a telephone interview. Fig. 2 shows the location of the data-loggers in Augsburg.

In Augsburg, there are almost 300 000 people living in an area of around 147 km^2. The base rate of population and sample size is shown in Table 2. During the latest available 30-year climate period, 1981–2010, there were six hot days (days with maximum temperatures exceeding 30 °C) per year on average. The annual mean temperature was 8.5 °C, with July being the hottest month (18.5 °C). The number of hot days has risen significantly in the past few years. In 2018 and 2019, there were already 12 hot days per year. The hottest day during the research period of this study was on 26 June 2019, with 34.4 °C measured at the official station of the German Weather Service (Deutscher Wetterdienst, DWD) at Augsburg-Mühlhausen. The average humidity during July and August 2019 was between 50 and 58% (Deutscher Wetterdienst, 2019). The outdoor air temperature (daily mean, minimum, maximum) for DWD weather station Augsburg-Mühlhausen for the past two years including the indication of the heat wave in July 2019 is shown in Fig. 3.

3.2. Dataset

From all loggers that were collected during October 2019, 554 data loggers could be unambiguously allocated and thus entered into further analyses. An initial quality control consisted of plausibility tests (eliminating values featuring unrealistically sudden changes in temperature and physically unrealistic values) and outlier tests (eliminating values outside the range defined by the twofold standard deviation around the mean estimated for running time windows); this led to the exclusion of roughly 2% of all 15-minute measurements. Fig. 4 gives an overview of the measured bedroom temperature over July and August 2019. The heat wave at the end of July is highlighted in orange, and outdoor air temperatures at the Augsburg-Mühlhausen DWD station are shown.

Since this study focuses on nocturnal temperatures, in general, bedrooms are expected to be occupied from 22:00 until 6:00 and high temperatures prevent tenants from having a good quality sleep; hence, only this time interval was analysed. Analysed temperatures were chosen from 24 July to 27 July 2019 because this was a three-day period with an extreme heat wave in the area of research (cf. Fig. 4). Fig. 5 shows the heat wave in greater detail with indoor and outdoor nocturnal air temperature during the heat wave as well as the days before and after.

In the accompanying survey, demographic and health-related information was asked about as well as such building characteristics as age, type and number of floors (cf. Table 3). Furthermore, there were questions about subjective heat stress perception and knowledge about health aspects of heat waves.

To statistically analyse significant differences among the groups of different variables, *t*-tests and one-way analyses of variance (ANOVAs) were conducted. Table 3 gives an overview of the variables and their values used for analysis in the descriptive statistics results section. Subjective heat stress was recorded by asking the participants about their perceived heat stress in 13 different situations. The situations were as follows: in general, at home during the day, at home during the night, doing housework, at work, on the way to work, while shopping, during leisure or sports activities, in parks or public gardens, in public transportation, in the respondent's car, in the respondent's neighbourhood and in the city centre. The participants were asked to answer the question for each situation on

Table 2
Base rate of population and sample size (Data source: Stadt Augsburg, Amt für Statistik und Stadtforschung, 2020).

Criteria	Total 2019	*n* in this study
Citizens	299,620	427
Female	151,301 (50.5%)	260 (60.9%)
Male	148,319 (49.5%)	167 (39.1%)
Under 18	45,661 (15.2%)	–
18–29	55,633 (18.6%)	97 (22.7%)
30–64	141,360 (47.2%)	263 (61.6%)
Above 65	56,966 (19%)	67 (15.7%)
People living alone	84,310 (28.1%)	152 (35.6%)

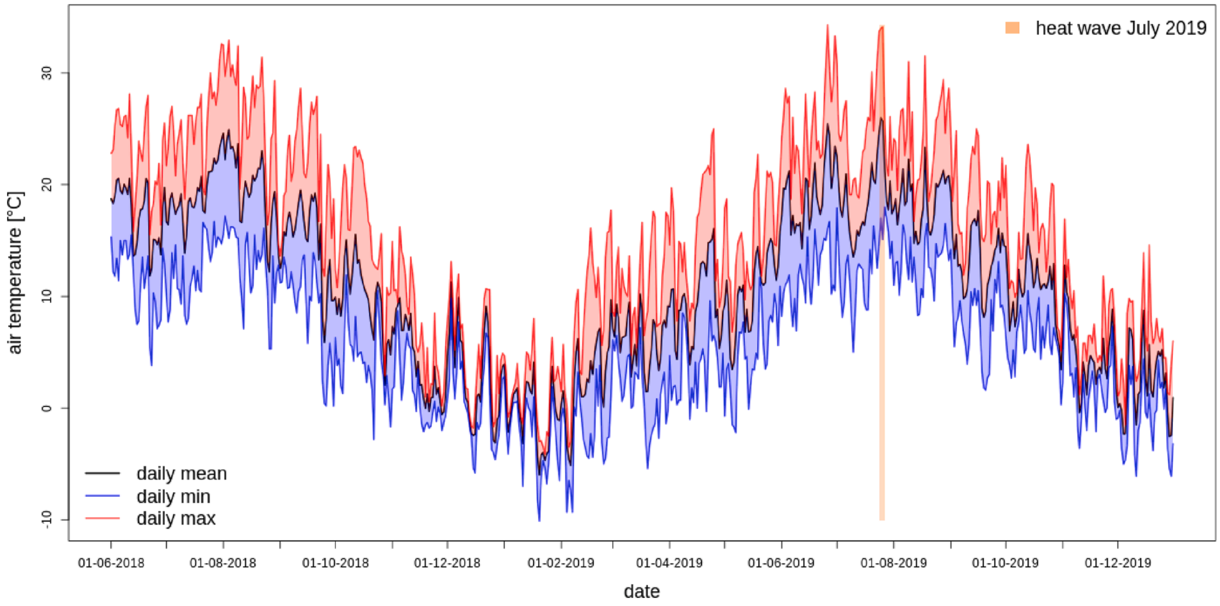

Fig. 3. Air temperature (daily mean, minimum, maximum) for the Augsburg-Mühlhausen DWD station (Data source: Deutscher Wetterdienst 2019). The heat wave at the end of July is indicated by the orange rectangle.

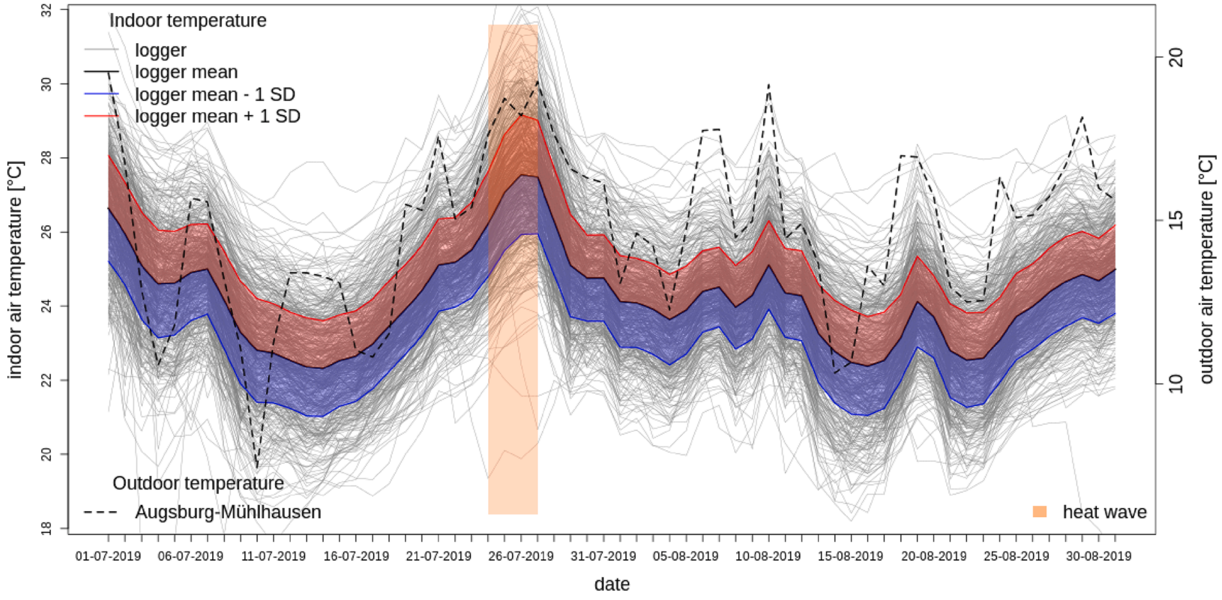

Fig. 4. Nocturnal (22:00 – 6:00) indoor and outdoor air temperatures in Augsburg during July and August 2019. Indoor air temperature is derived from the logger network described in the text. Outdoor air temperature is derived from the Augsburg-Mühlhausen DWD station (Data source: Deutscher Wetterdienst 2019). The heat wave at the end of July is indicated by the orange rectangle.

a 5-point Likert scale (1 = not at all, 2 = rather not, 3 = neutral, 4 = rather much, 5 = very much) with 0 being ‘not applicable’ if someone is never in the mentioned situation. For the current research question, the variable considered was subjective heat stress at home during night-time. The construct of subjective heat stress was adopted from the study of Kunz-Plapp et al. (2016), who investigated subjective heat stress factors in the city of Karlsruhe, Germany. In the present study, a health implication score is included in later analyses, generated from seven questions about experienced health implications during heat waves. The possible health implications included in the questionnaire were drowsiness, sleeping problems, concentration problems, vertigo, headache, nausea and cardiovascular problems.

New variables were coded from the mean nocturnal temperatures during a heat wave to analyse the personal heat stress perception between the exposed and non-exposed groups, as well as differentiated by vulnerable groups, including the following: 1) people aged

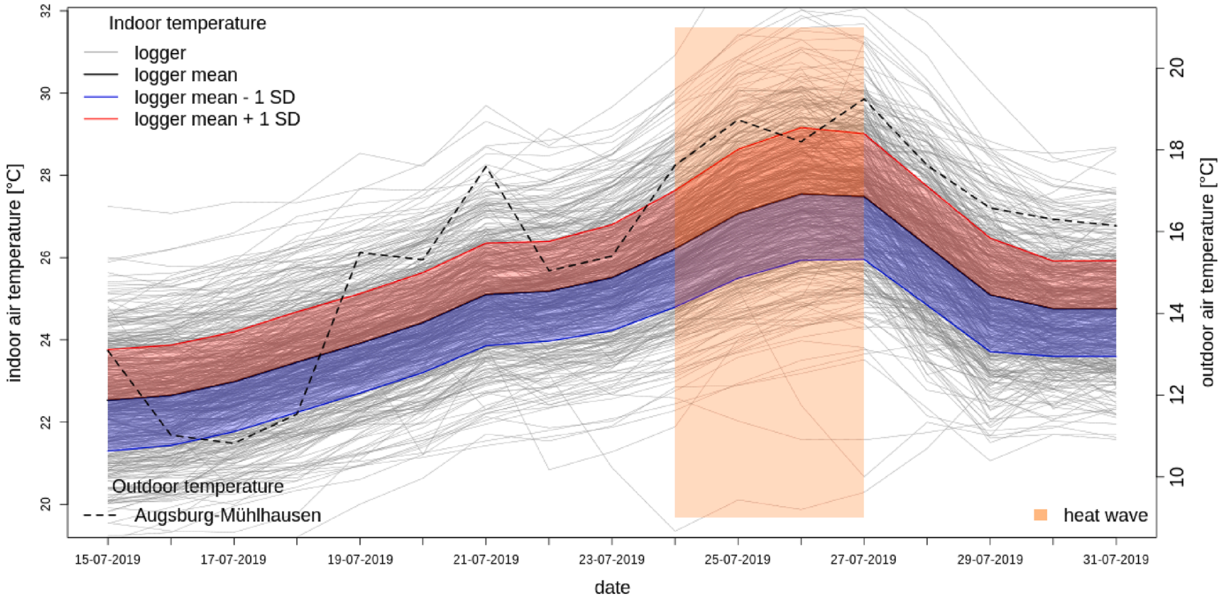

Fig. 5. Nocturnal (22:00 – 6:00) indoor and outdoor air temperature in Augsburg before, during and after the severe heat wave from 24 July until 27 July 2019 (indicated by the orange rectangle). Indoor air temperature is derived from the logger network described in the text. Outdoor air temperature is derived from the Augsburg-Mühlhausen DWD station (Data source: Deutscher Wetterdienst 2019).

Table 3
Overview of variables and categories used in analysis.

Sociodemographic Variable	Category
Health implication score	None (0)/moderate (1–4)/high (5–7)
Household with persons of 65 years and older	Yes/no
Gender	Male/female
Living alone	Yes/no
Number of persons living in household	1/2/3/4/5 or more
Employed	Yes/no
Number of adaptation measures taken at night (0–5 or more)	Using thin or no bedsheets/wearing thin or no clothes/taking a cold shower before going to bed/putting up wet clothes in the bedroom/sleeping with the window open or tilted/opening windows before going to bed/ sleeping in a cooler place
Feeling helpless (external locus of control)	Yes (score of 5–10)/no (score of 0–4)
Income	Under 1000€/1000€–3000€/3000€–5000€/>5000€ per month
Education	University diploma/no university diploma
Building-related variable	**Category**
Floor	Basement and ground floor/1st/2nd/3rd/4th and higher
Year built	Before 1919/1919–1948/1949–1971/1972–1980/1981–1990/1991–2000/2001 and more recent
Possibility to sit outside	Yes (balcony, terrace or garden)/No
Thermal insulation	Yes (wall or roof)/No
Local Climate Zone	Compact mid-rise/open mid-rise/open low rise/other (incl. large low rise, dense trees, low plants, bare soil or sand)
Type of house	Detached house/terraced house or semi-detached house/apartment house (3 to 6 apartments in house 7 to 12 apartments. in house (>12 apartments in house)
Ownership	Rented/own home
Temperature related	
Slope of regression line; Δ temperature regular days vs. heat wave	Low (0–0.3947)/middle (0.3948–0.514038)/high (0.514039–1)
Real mean nocturnal temperature during heat wave in °C	Low (below 26.7012)/middle (26.7013–27.9643)/high (27.9844 and higher)

65 years and older, 2) people with chronic disease and 3) people living alone with each variable being one temperature threshold (see section 4). The differentiation of vulnerable groups is adopted from the heat vulnerability literature (Birkmann et al., 2013; Cutter et al., 2003; Vellei et al., 2017). After the alignment of real bedroom temperature data with related survey data from the questionnaire, 427 data sets were included in the analysis.

4. Results

The following section first introduces descriptive statistics of mean nocturnal bedroom air temperature (t_{mnb}) and subjective heat stress at home, differentiated by socioeconomic and building-related characteristics. Afterwards, the results of the analyses regarding temperature thresholds for subjective heat stress at night are shown. The required sample sizes were determined beforehand for each test using GPOWER (Erdfelder et al., 1996), confidence interval of 95%, an error margin of 5% and a standard deviation of 50%.

4.1. Mean nocturnal temperature during heat wave and subjective heat stress

The overall mean nocturnal temperature (t_{mni}) during the three days of the July heat wave in the project was 27.38 °C (n = 554, sd = 1.57) and therefore 1.38 to 3.38 K higher than the threshold values depicted in most recommendations and standards in the background section. During the July heat wave 420 (98.4%) bedrooms in this study had a t_{mni} above 24 °C; 397 (93%) above 25 °C and 348 (81.5%) above 26 °C. The overview of t_{mni} can be found in Table 4.

Adding to the overview of mean nocturnal bedroom temperatures and various variables, below, the analysis considers relation of subjective heat stress at night with different socioeconomic and building-related factors. Table 5 gives an overview of the mean and standard deviation.

The one-way ANOVA shows significant ($p < .001$) results for people of 65 years and older ($F(1, 425) = 39.116; f = 0.3$). Note that effect sizes for the ANOVAs are given as f (Cohen, 1988). Employment status had a significant effect ($F(1, 425) = 11.995; p = .001; f = 0.17$) on subjective heat stress, employed people had a higher level of heat stress (3.32) than unemployed people did (2.89). The health implications (number of health conditions) during a heat wave showed significant results in the ANOVA ($F(2, 424) = 42{,}928; p < .001; f = 0.45$), and Tukey post hoc analysis revealed a significant difference between all groups. The number of adaptation measures taken was significant ($F(6, 420) = 2{,}236; p = .011; f = 0.18$), with people taking one or two adaptation measures at night reporting the lowest heat stress levels (2.73 and 2.83). The LCZ had a significant effect ($F(3, 415) = 9.769; p = .011; f = 0.15$) on subjective heat stress. People living in 'compact mid-rise' areas had the highest mean heat stress (3.48). The dwelling type had significant results in the one-way ANOVA ($F(4, 422) = 2.404; p = .049; f = 0.15$) with the lowest heat stress levels among people living in detached houses (2.84) and terraced or semi-detached houses (2.94). The highest heat stress levels were found among people living in apartment houses with three to six units (3.38). Significant results ($F(9, 417) = 2.167; p = .006; f = 0.24$) were also found for the number of adaptation equipment features in the apartment. People with nine and more features reported the lowest heat stress level (2.77) while people with none and one feature had the highest heat stress levels (3.67 and 3.65). The number of pieces of shadowing equipment was also significant ($F(3, 423) = 2{,}745; p = .043; f = 0.14$). People with three or more features to shadow their apartment had the lowest heat stress level (2.73), while people with zero and one shadowing feature had the highest (3.26 and 3.28). Another significant result was found for the year the building was built ($F(6, 420) = 2{,}401; p = .027; f = 0.18$). People living in houses built in 2001 and later reported the lowest heat stress level (2.61), and people living in houses built before 1919 reported the highest (3.43). Subjective heat stress level was lowest (2.88) among people living in the basement or on the ground floor and highest (3.36 and 3.32) among people living on the third and fourth or higher floors ($F(4, 422) = 2{,}657; p = .032; f = 0.16$).

People in rented homes had a significantly ($p < .001$) higher level of heat stress (3.38) than people living in an apartment or house that they own (2.75; $F(2, 424) = 14{,}745; p < .001; f = 0.26$). One-way ANOVA showed significant results ($F(2, 422) = 133.393; p = .004; f = 0.16$) between the groups, with people living in apartments with the highest regression of temperature showing the highest subjective heat stress (3.45; middle = 3.19; low = 2.99). The post hoc Tukey test revealed a significant difference ($p = .004$) between the group with the lowest and highest slopes of temperature increase.

The measured mean temperatures at night during the heat wave also showed a significant result ($F(2, 424) = 17.540; p < .001; f = 0.29$) between the tertile groups of high, middle and low temperatures and their subjective heat stress at night. As expected, the results in Table 5 show the highest subjective heat stress for the group with the highest mean temperature (3.58), whereas it shows lowest subjective heat stress for people living in apartments with the lowest mean temperature (2.8).

No significant results were found for different genders, different numbers of people living in a household, people living alone or people feeling helpless. Furthermore, no significance was found for the variables of income, education, number of rooms and possibility to sit outside.

Table 4
Overview occurrence of mean nocturnal temperatures.

Temperature	*n*
Below 24 °C	7
24–25 °C	23
25–26 °C	48
26–27 °C	97
27–28 °C	111
28–29 °C	81
Above 29 °C	60
Total	427

Table 5
Overview of subjective heat stress at night at home.

		Subjective heat stress at night at home	
	n	Mean	Standard deviation
Health implication during heat wave			
None	21	1.48	0.6
Moderate	307	3.13	1.1
High	99	3.77	1.0
Household with persons of 65 years or older			
Yes	70	2.44	1.13
No	357	3.35	1.1
Employed			
Yes	309	3.32	1.08
No	118	2.89	1.29
Number of adaptation measures taken			
1	22	2.73	0.71
2	60	2.83	1.08
3	179	3.34	1.29
4	125	3.21	1.1
5 or more	41	3.34	1.38
Feeling helpless			
Yes	162	3.29	1.11
No	265	3.14	1.17
Living alone			
Yes	152	3.13	1.26
No	275	3.24	1.1
Education			
University degree	251	3.14	1.15
No university degree	176	3.28	1.17
Building-related characteristics			
Floor			
Basement and ground floor	99	2.88	1.1
1	112	3.3	1.08
2	103	3.23	1.2
3	75	3.36	1.14
4 and higher	38	3.32	1.3
Year built			
before 1919	103	3.43	1.07
1919–1948	49	3.18	1.13
1949–1971	115	3.14	1.19
1972–1980	64	3.3	1.29
1981–1990	34	3.06	0.98
1991–2000	29	3.28	0.84
2001 and later	33	2.61	1.27
Possibility to sit outside			
Yes	151	3.22	1.16
No	274	3.19	1.16
Thermal insulation			
Yes	76	2.86	1.09
No	195	3.26	1.14
Local Climate Zone			
Compact mid rise	94	3.48	1.14
Open mid rise	254	3.17	1.14
Open low rise	66	2.98	1.12
Other	5	2.6	1.82
Type of house			
Detached house	19	2.84	1.39
Terraced or semi-detached house	47	2.94	1.29
Apartment house (3 to 6)	142	3.38	1.04
Apartment house (7 to 12)	155	3.23	1.13
Apartment house (>12)	64	3.02	1.24
Ownership			
Rented	304	3.38	1.12
Owned home	120	2.75	1.12
Temperature-related	*n*	Mean	Standard deviation
Slope of regression line; delta temperature regular days vs. heat wave			
Low			
Middle	138	2.99	1.16

(*continued on next page*)

Table 5 (*continued*)

Temperature-related	*n*	Mean	Standard deviation
High	148	3.19	1.08
	139	3.45	1.17
Actual mean temperature during heat wave			
Low	142	2.8	1.14
Middle	143	3.21	1.07
High	142	3.58	1.13

4.2. *Factors for subjective heat stress*

To find out about influencing factors for subjective heat stress in this study, Pearson correlation was conducted, the results are given in Table 6 for socioeconomic factors and Table 7 for building- and temperature-related factors. The required sample size was 138. Based on the results of this study, as presented in Table 6, subjective heat stress is related to health implication occurring during a heat wave ($r = 0.377; p < .001$), to being 65 years or older ($r = -0.29; p < .001$) and to being employed ($r = 0.166; p < .001$). The number of adaptation actions taken at home also shows a significant effect ($r = 0.113$; $p = .019$). No significant correlation was found for the factors of feeling helpless ($p = .203$), living alone ($p = .37$) or education ($p = .203$).

Table 7 shows correlations regarding the building- and temperature-related factors. Based on the results of this study, subjective heat stress is related to the floor level of the apartment ($r = 0.134$; $p = .006$), the age of the building ($r = -0.134$; $p = .005$) and the thermal insulation ($r = 0.158; p = .009$). Furthermore, the LCZ shows a significant effect on subjective heat stress ($r = 0.147$; $\mathrm{p} = .003$) as does ownership status ($r = 0.255; p < .001$). Both temperature-related factors are associated with subjective heat stress—the slope of temperature regression ($r = 0.16$; $p = .001$) and the indoor temperature during a heat wave ($r = 0.276$; $p < .001$).

Multiple linear regression was conducted to predict subjective heat stress based on the significant identified variables in the correlation analyses. The required sample size for the regression analysis was 40. A significant regression equation was found ($F(11,251) = 11.554$, $p < .001$) with an R^2 of 0.336. The regression model is shown in Table 8. According to the model, significant predictors of subjective heat stress at home are the health implications suffered during a heat wave, being younger than 65 years, the LCZ the apartment is located in and the indoor temperature during a heat wave.

4.3. *Temperature thresholds for subjective heat stress*

Table 4 shows the real temperatures measured to give an overview of mean nocturnal temperatures during a heat wave in the study apartments. Most apartment in this study can be counted as overheated, no matter which of the identified thresholds is used. Of course, the t_{nmi} is a static measure, and most recommendations introduced in section 2.3 are dynamic models. However, in comparison with the threshold chosen by the court decision in Germany in 2006 (25 °C) and the WHO threshold for bedrooms (24 °C), it is clear that, for the former, around 93% of the bedrooms in the study are too hot during the heat wave at night, and for the latter, the proportion reaches 98%.

The mean of subjective heat stress at night for all survey participants is 3.21 ($N = 427$; $\mathrm{sd} = 1.15$). To assess the effect of different temperature levels on heat stress at night, unpaired *t*-tests were conducted for different bedroom temperature thresholds. This allowed identifying those temperatures at which a certain group of people, from a statistical point of view, starts reporting that they feel significantly stressed by heat. New variables were coded regarding different overheating thresholds (mean temperature at night from 24.8 °C to 28 °C). Only two bedrooms had a mean temperature during the heat wave of 23 °C or below; therefore, the analysis started at 24 °C.

In addition to the analysis of the whole group of participants ($N = 427$), the groups investigated were divided into the following categories:

(1) People living alone ($n = 152$);
(2) Non-vulnerable people ($n = 292$), that is, people younger than 65 and without chronic health conditions;

Table 6
Pearson correlation among all socioeconomic variables.

Variable	1	2	3	4	5	6	7
1. Subjective heat stress							
2. Health implication	0.377**						
3. Older than 64	−0.29**	−0.164**					
4. Employment	0.166**	−0.04	−0.525**				
5. No. of adapt. actions	0.113*	0.151**	−0.133*	0.009			
6. Feeling helpless	0.062	0.143**	0.061	−0.018	0.037		
7. Living alone	0.043	0.036	0.129*	0.102*	0.102*	0.040	
8. Education	−0.062	−0.058	−0.234*	0.216*	0.216*	−0.179**	−0.18**

Note: **: significant at < 0.001 level; *: significant at 0.05 level.

Table 7
Pearson correlations of all building- and temperature-related variables and subjective heat stress.

Variables	1	2	3	4	5	6	7	8	9
1. Subjective heat stress									
2. Floor number	0.134**								
3. Year building was built	−0.134**	−0.092*							
4. Possibility to sit outside	0.013	0.275***	0.097*						
5. Thermal insulation	0.158**	0.009	0.377***	0.111					
6. LCZ	0.147**	0.110*	0.254***	0.09	0.095				
7. Type of house	0.042	0.303***	0.116*	0.316***	0.005	−0.049			
8. Ownership	0.255**	0.176***	0.24***	0.096*	0.226***	0.15**	−0.287***		
9. Slope of temperature regression	0.16**	0.227***	−0.338***	−0.109	−0.236***	−0.171**	−0.164**	−0.163**	
10. Temperature in bedroom during	0.276***	0.449***	−0.212***	−0.068	−0.182**	−0.198**	−0.033	−0.201***	0.598**

Note: *** significant at < 0.001 level; **: significant at 0.01 level; *: significant at 0.05 level.

Table 8
Regression analysis of subjective heat stress at home during night-time.

Model summary: $R^2 = 0.580$; $R^2_{adj} = 0.336$, $F = 11.554$, $p < .001$. Dependent variable: Subjective heat stress at home during night-time.

Variable	Unstandardized β	Standard Error	Standardized β	t
Health implication score	0.849	0.125	0.371	6.79***
Age over 64	−0.276	0.118	−0.145	−2.346**
Employed				ns
Number of adaptation measures taken				ns
Floor number				ns
Year building was built				ns
Thermal insulation				ns
LCZ	−0.159	0.094	0.093	1.693*
Ownership				ns
Slope of temp. regression				ns
Indoor temperature	0.271	0.1	0.195	2.705**

Note: method: Enter; ns = not significant; *** significant at 0.001 level; ** significant at 0.05 level; * significant at 0.1 level.

(3) Exposed people ($n = 264$), that is, living on a high floor (above the fourth floor) or in the most affected climate zones (i.e., compact mid-rise or large low-rise climate zone);
(4) People with chronic diseases ($n = 87$; regardless of age); and
(5) People with the highest slope of regression line (temperature increase during heatwave; $n = 139$).

Each of the groups analysed is considered vulnerable (following previous studies such as Seebass, 2017). The results are expected to show significant differences at various temperature thresholds between 24 °C and 27 °C degrees because these are the thresholds identified in section 2.3. Having chronic diseases and living alone is an issue when it comes to health impacts, as all of those groups require a higher amount of attention and counter measures compared with young, healthy people. Those groups are expected to have the lowest temperature threshold when it comes to subjective heat stress, which means they can ask for help early enough when they

Table 9
Results of unpaired *t*-tests for different temperature thresholds with subjective heat stress variables.

Results for	Temp. threshold	n	M	sd	Statistics	r
Whole group ($n = 427$)	≤24.9 °C	24	2.75	1.33	$t = 1.968$*	0.1
	>24.9 °C	403	3.23	1.14		
Non-vulnerable group ($n = 292$)	≤25.7 °C	32	2.94	1.06	$t = 2.037$*	0.13
People younger than 65 and without chronic health condition	>25.7 °C	260	3.35	1.02		
People living alone ($n = 152$)	≤24.2 °C	4	1.75	0.96	$Z^a = 2.173$*	0.18
	>24.2 °C	148	3.17	1.24		
People with chronic disease(s) ($n = 87$)	≤26.7 °C	30	3.00	1.41	$t = 2.019$*	0.21
	>26.7 °C	57	3.56	1.13		
Exposed group ($n = 264$)	≤26.3 °C	39	2.74	1.37	$t = 3.139$*	0.19
Living on high floor (above 4th) or in the most affected LCZ (i.e. compact mid-rise or large low-rise)	>26.3 °C	225	3.38	1.14		
Group with the highest slope of temperature regression ($n = 139$)	≤26.2 °C	7	2.57	1.4	$Z^a = 1.843$*	0.16
	>26.2 °C	132	3.49	1.14		

* $p \leq 0.05$; Z^a = Mann-Whitney-*U* test (data not normally distributed); *M* = mean; *sd* = standard deviation; *r* = Pearson's correlation coefficient.

feel stressed during a heat wave. It is expected for non-vulnerable people to have the highest threshold for subjective heat stress because they are the least endangered. The same expected results are raised for the groups of people who are specifically exposed to heat waves and the group with the highest regression slope of temperature because they might already have adapted physically to high temperatures and are accustomed to such conditions.

Data were normally distributed for each group (Shapiro–Wilk test, $p > .05$), so *t*-tests could be conducted. Exceptions were applied for the group of people living alone and people with the highest slope of temperature increase, for which the Mann–Whitney–*U* test was chosen. The required total sample size was 45. All variables showed homogeneity of variance (Levene's test, $p > .05$).

Table 9 shows the detailed results of the thresholds where the tests were significant, including means, standard deviations and effect sizes for every group tested.

The unpaired *t*-test for the whole group showed a significant result at the $p \leq 0.05$ level at 24.9 °C ($t(425) = 1.968$), meaning the group of people living in apartments with a mean temperature of 24.9 °C and above at night reported a significantly higher level of heat stress (Mean (M) = 3.23, $sd = 1.14$) than did the group with a mean temperature up to 24.9 °C ($M = 2.75$, $sd = 1.33$). The effect size, calculated as Pearson's correlation coefficient (r) for this analysis ($r = 0.1$) was found to be small (Cohen, 1988).

The lowest significant value found was 24.2 °C, in the group of people living alone. This means, that, among people living alone, there is a significant difference in subjective heat stress at night between people sleeping in bedrooms with a nocturnal mean bedroom temperature up to 24.2 °C compared with those living in bedrooms with a $t_{mnb} > 24.2$ °C. The effect size is small to moderate ($r = 0.18$; Cohen, 1988). The expectation for the group of people living alone to have a lower threshold for subjective heat stress was fulfilled.

For the group of non-vulnerable households, there was a significant difference ($p \leq 0.05$) in subjective nocturnal heat stress at a threshold of 25.7 °C ($t(88) = 2.052$; $r = 0.13$), indicating a small effect. The results indicate that non-vulnerable people living in apartments with mean nocturnal bedroom temperatures of 25.7 °C or more ($M = 3.35$; $sd = 1.02$) reported significantly higher heat stress than the group with lower temperature conditions ($M = 2.94$; $sd = 1.06$). Therefore, the expectation that the non-vulnerable group would have a higher threshold compared with people with chronic disease(s) or the exposed group could not be fulfilled unrestrictedly.

People who were particularly exposed to high temperatures reported significantly higher subjective heat stress for temperatures of 26.3 °C and above ($M = 2.74$; $sd = 1.37$) compared to people with lower temperatures during night-time ($M = 3.38$; $sd = 1.14$; $t(262) = 3.139$; $p = .002$). The effect size was small to moderate ($r = 0.19$). Therefore, the expectation of people being exposed to heat waves having a higher threshold of subjective heat stress could be fulfilled, like for people living in apartments with the highest rise in temperature regression, who reported significantly higher subjective heat stress at night at the threshold of 26.2 °C.

The highest threshold regarding nocturnal heat stress was found for the group of people with chronic disease ($t(65) = 2.012$, $p = .047$). Here, a significant difference in subjective heat stress was found for people living in apartments of 26.7 °C and above ($M = 3.56$; $sd = 1.13$) compared with the group having lower temperatures ($M = 3.00$; $sd = 1.14$). The effect size is small to moderate ($r = 0.21$; Cohen, 1988). This is an unexpected result because it was anticipated that, due to their higher vulnerability, people with chronic diseases would have a lower temperature threshold for subjective heat stress.

5. Discussion

The bedroom temperature during a heatwave in the analysed period shows that overheating is already a problem, although Augsburg belongs to the least affected towns in Germany. To understand the adequacy of an overheating threshold for southern Germany and in general, it is important to identify the temperature at which people feel stressed at home.

To reveal influencing factors on subjective heat stress at home during night-time, regression analysis was conducted. In contrast to results from Sebass et al. (2017) and Borchers et al. (2019), in this study, it was found that older people were not the ones experiencing higher levels of *subjective* heat stress, but instead, the younger people were. However, this perception on the part of vulnerable groups can be identified as a problem. In this study, 53 (69.7%) of the people 65 years and older suffered at least one health effect during heat waves, which can lead to serious life-threatening conditions; however, they did not see their vulnerability as such and might not take action to adapt to heat waves to protect their health. These results align with the findings about vulnerability (e.g., Großmann et al., 2012) and subjective heat risk perception in previous studies (Beckmann and Hiete, 2020) where older people feel less affected by high temperatures than younger people do (age 18–64). Suffering from more profound health implications, such as headaches, circulatory problems or concentration disorders during a heat wave is an additional factor for higher subjective heat stress, which aligns with the results of Borchers et al. (2019), Kunz-Plapp et al. (2016) and Sebass et al. (2017). Regarding the LCZ, people living in compact mid-rise areas reported the highest subjective heat stress. In studies of Seebass (2017) and Franck et al. (2013), urban structures did not have an effect on subjective heat stress, whereas Kunz-Plapp et al. (2016) and Großmann et al. (2012) found that urban structures did have significant influence. However, none of the previous studies used the rather objective scheme of LCZ to differentiate between building structures and density in their research area. It remains unclear whether the UHI effect is the main driver, or whether it is that a lack of green spaces affects perception or that, in more densely populated areas, more people live in apartments on upper floors. The results must be interpreted with great care because, in the study area, LCZ is also linked to building age and likely also to adaptation measures. Indeed, the subjective heat stress level is lowest in people living in the basement or on the ground floor and highest among people living on the third, fourth or upper floors, although the floor did not have a significant influence on subjective heat stress in the final regression model. In their studies, Seebass (2017) and Großmann et al. (2012) found significantly higher heat stress levels among people living on higher floors or under the roof; however, our ANOVA results show that the heat stress level is slightly higher on the third floor than it is on the fourth floor or higher. This could be related to the building structure in the city of Augsburg.

Nocturnal bedroom temperatures play a key role in the recovery of the human body. The overall mean nocturnal temperature during the heatwave in July 2019 analysed in the project was 27.38 °C, and therefore, 3.38 to 1.38 K higher than most recommendations and standards presented in the background section imply. When taking the highest temperature threshold of 26 °C into account, 348 bedrooms (81.5%) were overheated during the July heatwave. When interpreting these data, care must be taken, as we expect a particular interest to participate in the study among those households for which heat stress is a topic of perceived interest. Still, at first glance, the findings may be interpreted showing the need for a different threshold for Germany (or parts thereof) than for the United Kingdom because the large number of exceedances would otherwise show that many households are heat stressed without much differentiation. A solution could be to add a further temperature for severe heat stress or differentiate further based on findings from health-related research (Esplin et al., 2019; Estoque et al., 2020; Wang et al., 2020), such as by combining temperature and humidity information or the period over which temperatures are exceeded.

The results in Table 9 show that subjective heat stress levels at night are significantly higher when the bedrooms' mean temperature during a heatwave is above 26.4 °C for the whole group of participants, as well as for the non-vulnerable group. The highest threshold regarding nocturnal heat stress was found for the group of people with chronic disease(s). Here, a significant difference was found at 26.7 °C, meaning their subjective heat stress starts at a higher threshold. However, this also poses a problem: People suffering from chronic diseases do not feel significantly stressed by high temperatures if they remain below 26.7 °C, and therefore, do not feel the urge to take adequate adaptation measures to protect themselves from severe health impacts caused by heat.

The key strengths of the study are the dataset of 427 temperature dataloggers, on the one hand, and here in particular, the exceptional situation of having access to bedroom temperatures with a 15 min resolution during a heatwave, and on the other hand, the accompanying survey with sociodemographic and building-related data collected in private households all over the city of Augsburg, that is, covering a wide range of settings. The summer months in 2019 were among the hottest recorded so far in Augsburg, but temperature records have a low duration under current climate change in Germany (IPCC, 2019). The analysis gives exact statistical thresholds for vulnerable and non-vulnerable households when it comes to significantly higher heat stress, underlining results from previous studies. These thresholds may be used for developing heat action plans.

A limitation of this study is that temperature data were not measured over a whole year, whereas many recommendations refer to an amount of overheating time during a one-year period. Furthermore, temperature was only analysed for one heatwave during July 2019. This does not lead to an overall picture of the overheating situation in Augsburg. Further, we cannot exclude that people who agreed to participate are more sensitised to the problem of heat stress because of higher bedroom temperatures (i.e. there is a bias in the sample participants). However, the building-related data show a variety of climate zones in Augsburg, and all floor levels, building types and so on are covered, making us confident that any bias—which is inherent in any study—is sufficiently small that it did not affect the outcomes of our research. The survey was conducted in July 2019. We cannot exclude that the same survey would have resulted in slightly different answers if conducted in a different month or season. Another limitation arises from the construct used to measure subjective heat stress. Although the scale has been used in past studies, there is inaccuracy in information based on feelings and perception. However, in the social sciences, data often rely on self-reported data, and similarities to previous studies imply that the bias from the reported construct is rather small. Limitations are also caused by the sample size and dispersion of data, which in the study lead to significant results; however, they should be regarded critically as the results only apply to the participants investigated in this study and effect sizes often are small. Finally, although the temperature datalogger has an indicated accuracy of ± 0.5 °C (Elitech 2020), measurement problems might always be an issue. In particular, positioning of the datalogger in the bedroom remains an issue. However, a brief and clear installation guide provided with the datalogger and a quality assessment of the data collected make us confident that the temperature measures are good approximations of the real nocturnal bedroom temperatures, making this data rather unique and of the highest value for heat stress analyses.

Future research should investigate why certain groups of people feel subjectively more heat stressed than others do and which factors contribute to subjective heat stress. Furthermore, it is important to develop a statistical model to define factors influencing indoor temperature during heatwaves in certain environments and for certain types of buildings to better predict vulnerable and more strongly threatened people and prevent them from being harmed by heat exposure. Finally, people think, behave and feel differently in different areas, such that a repetition of the analysis in other towns would be worthwhile.

6. Conclusion

Climate change is expected to cause rising temperatures and an increasing number of hot days in the future. People living in urban areas will be most affected by more frequent heatwaves because the UHI effect is increasing heat exposure and leading to more tropical nights. High temperatures at night contribute to severe heat stress and affect human health. To better understand heat perception and overcome these health threats, it is necessary to investigate subjective heat stress and its influencing factors. This paper answered the following research questions: Which factors are related to subjective heat stress of occupants in the city of Augsburg at night? At which night-time indoor temperatures do people start feeling heat stressed?

Background was given on subjective heat stress, and existing temperature thresholds were collected from the literature. The study was based on temperature and survey data collected in Augsburg, Germany, in the summer of 2019 from 427 households. The results showed that 81.5% of the bedrooms in this study exceeded the commonly used threshold of 26 °C during a heatwave. This implies that there is an urgent need for heat adaptation in private households, especially in bedrooms.

A problem identified in the study was that older people did not feel as stressed by heat as younger people did, despite suffering from health implications during heatwaves. Therefore, they might not see the need for heat risk prevention, underlining the term 'silent killer' for heatwaves. Looking at the temperature thresholds for people with diseases and non-vulnerable people underlines this problem. The results for the whole group of participants showed that for bedrooms' mean nocturnal temperature above 26.4 °C during a heatwave, the heat stress level is significantly higher than below 26.4 °C. This identified threshold is highest (26.7 °C) among people suffering from chronic disease(s).

By combining real temperature data and reported perception, this study identified thresholds that help communities in developing heat action plans. It can give guidance to authorities on the point at which action is necessary, and it represents an important step towards heat management. The results also point out the need for more private heat adaptation measures combined with more intensive risk communication to vulnerable people, especially the elderly and people with chronic diseases.

7. Notes

The statistical tests were chosen to determine whether the means of the tested groups were different. While ANOVA can determine the difference of means between three or more groups, a *t*-test was used for variables with two groups. Whenever applicable, as when the requirements for ANOVA or the *t*-test were not met, the Mann–Whitney *U* test (when data were not normally distributed) were conducted. Correlation analyses showed correlations between variables, resulting in significant factors used for the regression model in the last step.

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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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