Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-03091-5 OPEN

Understanding individual heat exposure through interdisciplinary research on thermoception

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Extreme heat events are more frequent and more intense globally due to climate change. The urban environment is an additional factor enhancing the effects of heat. Adults above 65 years old are especially at risk due to their poorer health, physiology and socio-economic situation. Yet, there is limited knowledge about their experiences of summer heat, their actual heat exposure and how they negotiate their thermal comfort through different adaptation practices. In conventional research on heat exposure and thermal comfort, very little attention is given to individual behaviour and subjective experiences. To understand how older adults feel the heat in the city we study their thermoception, which we conceptualise as an embodied knowledge about bodily sensations, thermal environments and adjustments to heat. This article stems from interdisciplinary research conducted in Warsaw and Madrid in the summers of 2021–2022. We combine and juxtapose data from ethnographic research and from physical measurements of temperature gathered in people's homes, to show on a microscale how we can study and understand the diversity in individual heat exposure more holistically. We demonstrate that to understand the consequences of heat for vulnerable populations it is crucial to study thermoception, the subjective experiences of heat, in addition to analysing their thermal environments. With the use of a unique methodology, this article shows how similar weather conditions are experienced differently by people from the same cities, depending on the materiality of their dwellings, availability of cooling devices, as well as everyday habits and their individual bodies. We discuss the social, material and temporal adjustments participants made to deal with heat, to showcase their agency in affecting their individual heat exposure. The article emphasises the role of social sciences and qualitative methods in research on individual heat exposure and argues for the co-production of knowledge on the topic.

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Introduction

Heat exposure is increasingly becoming a daily experience for many people. In the latest IPCC report (Pörtner et al., 2022), extreme heat events and heat stress are listed as the main hazards that will keep increasing, affecting people's health and wellbeing. This affects the hottest areas of the globe which become unliveable (ibid.), as well as Europe, which has been recently identified as a 'hotspot' in the northern hemisphere (Rousi et al., 2022). Varied groups of people are affected differently by heat stress, with adults above 65 years old, babies, and people living in difficult socio-economic situations most at risk (Basu, 2009). This article studies the experiences of urban heat among older adults living in two European cities.

Research on individual heat exposure can be divided into three strands. One perspective studies thermal environments and focuses more on *heat exposure*. This has been done mainly by biophysical and environmental sciences (e.g., Lucchese et al., 2016; Kuchcik et al., 2021). Another perspective studies people's perceptions of and reactions to high temperatures, it focuses more on *individual heat*. This has been done primarily by social sciences (e.g., Klinenberg, 2015; De Vet and Head, 2020; Kobi, 2023). The third approach aims to combine the two perspectives and account for both thermal environments and people's reactions and adaptation to it, to get a more holistic understanding of *individual heat exposure* (e.g., Kuras et al., 2017; Hass and Ellis, 2019; Nazarian, Lee (2021)).

A limited understanding of individual behaviour related to hot weather has been identified as the main drawback in research on heat exposure (Nazarian, Lee (2021); Vargas et al., 2023). This affects policy, as most adaptation policies are based solely on quantifiable temperature readings and top-down analysis (WHO, 2021). The tools the governments currently provide for citizens to deal with heat, like insulation policies or heatwave alert systems, provide one-size-fits-all solutions and do not account for individual diversity in heat exposure. People's reactions to heat and their adaptation strategies are varied and complex, shaped by their different preferences, routines, social networks, access to resources, and inter/intra-house mobility (Hass and Ellis, 2019; Kuras et al., 2017; Seebaß, 2017). However, within that third strand of research, the focus so far has been mainly quantitative (e.g., Kántor et al., 2016; Wang et al., 2018; Beckmann et al. (2021); Chen et al., 2022), which cannot adequately grasp the individual experience. The individual differences in human perception of temperature are already an established fact (e.g., Bernhard et al., 2015; Kuras et al., 2015), but the reasons for these differences are still unclear (Schweiker et al., 2018) and require the implementation of qualitative methods (Hass and Ellis, 2019; Hass, Runkle and Sugg, 2021).

This article is based on interdisciplinary research that combined ethnographic methods with the use of sensors and regular measurements of temperature in people's flats. The research was conducted over two consecutive summers, in 2021 and 2022, in Madrid and Warsaw. It included 10 research participants in each city who were above 65 years old. The sample size was small to enable the application of qualitative methods, such as long-term participant observation, and to explore the implementation of this unique methodology on a small scale.

We argue that what accounts for diversity in heat exposure is not only people's thermal environments, but also their individual thermoception. We define thermoception as a form of embodied knowledge that relates to people's bodily sensations, perceptions, actions and adjustments to heat implemented both with and within their bodies and in their environments. Embodied knowledge is a type of knowledge that is not necessarily reflected upon or conscious, it is deeply sensorial and "the knowledge-making is a dynamic process arising directly from the indissoluble relations that exist between minds, bodies, and environment" (Marchand, 2010: 2; see also Lock, 1993; Ignatow, 2007; Wallenborn and Wilhite, 2014). To access this type of knowledge, we traced different social, temporal and material adjustments participants made in their daily lives. In this article we combine and juxtapose the scientific knowledge from the sensors' temperature readings with older adults' knowledge about their bodies, environments and heat, to study individual heat exposure from a more holistic and bottom-up perspective.

This introduction is followed by a review of literature. We then present our conceptual approach, methodology, and findings, which are structured into two sections: socio-material adjustments and socio-temporal adjustments. In the Discussion we focus on the recognition of older adults' agency and thermoception which explain the diversity of individual heat exposure.

Literature review

Research on heat exposure has been a domain of environmental and biomedical sciences that focus mainly on associated health risks and mortality (e.g., Kovats and Hajat, 2008; Kuras et al., 2017) and thermal comfort (e.g., Wang et al., 2018; Mazzone and Khosla, 2021). The issue of thermal comfort and discomfort has also been studied by architects (e.g., Barber, 2019, 2020; Roesler, Kobi and Stieger, 2022). Moreover, geographers have studied individual heat exposure, for instance by analysing people's perceptions of extreme heat risks and related behaviours (e.g., Howe et al., 2019; Goldstein and Howe, 2020) and their daily adaptation practices (e.g., Oppermann et al. (2018)). In comparison, the focus on heat in social sciences, except for geography, and humanities has been smaller, with two major works analysing the socio-political causes and effects of heatwaves in 1995 in Chicago (Klinenberg, 2015) and in 2003 in Paris (Keller, 2015).

Research on heat exposure to a large extent relies on measuring the thermal environment (e.g., Kuchcik et al., 2021). However, there is an increasing recognition that such thermal indices as the Universal Thermal Climate Index (UTCI), which uses air temperature, wind, radiation, and humidity to evaluate bodily thermal stress, do not properly account for people's perceptions of heat (e.g., Lucchese et al., 2016). When asked about their thermal experiences, people's answers differ from the measurements of temperature and model predictions, and also between each other (e.g., Kántor et al., 2012; Chen et al., 2022). The location, time of the year and where a person lived previously matter for how people feel in similar thermal environmental conditions (Kántor et al., 2016). Also, their mood, convictions, surrounding view impact people's experiences of temperature (Wang et al., 2018). As Okyere and Lin (2023) suggest, life dissatisfaction, food insecurity, gender and physical disabilities affect people's vulnerability and their ability to cope with thermal stress (see also Seebaß, 2017). Furthermore, Esplin et al. (2019) demonstrate that the individual experience with heat-related health symptoms strongly predicted all reported heat protective behaviours, while measured heat exposure had a much weaker influence. Thus, showing that measuring only the thermal environment is not enough to understand how people feel and react to heat. Moreover, as Beckmann et al. (2021) show, age strongly affects the perception of heat. Older adults are particularly vulnerable to heat stress because their thermoregulation changes with age (Broczek, 2021) and they are less inclined to notice thermal and physical strain on their bodies (Millyard et al., 2020). They also have less social support (Klinenberg, 2015).

People adjust and react to heat based on their thermoception, or somatic work, as Vannini et al. (2012) put it. Being too hot or too cold drives many adaptation practices. According to Ong

(2012), the sense of heat and maintaining homeostasis "is one of the most important senses we have in keeping us alive" (2012: 6). Thermoception is indeed treated by some (Ong, 2012; Lara, 2015) as a fifth sense (see also McNarry et al., 2021). There are also several studies showcasing what role particular senses play in understanding temperature and heat, for instance taste (Kantor, 2019), hearing and smell (Royston, 2014) or sight (Starosielski, 2019, 2021).

Psychophysics has studied the relationship between physical stimuli (such as light, sound, or temperature) and our perceptual experiences, quantifying how our sensory systems respond to different stimuli and how we perceive them (see Fechner, 1860 and Weber, 1846). These studies have been useful to determine the smallest changes in a stimulus that we can detect. However, it has been shown there is an epistemological mistake in establishing a functional relation between stimulus and sensation (Giovanelli, 2017; see also Savage, 1970 and Cassirer, 1923). Research on psychophysics continues to question its ability to quantify the different dimensions of sensations and increasingly focus on the creative and social aspects of the sensory experience (see Fretwell, 2020 and Ouzounian, 2021).

In a similar approach, we understand thermoception to be more than a sense, but also a form of sensory and embodied knowledge. We build on Vannini et al. (2014), who argued for understanding thermoception also as a set of activities people might get involved in. They found out that the capacity to act of people living in off-grid houses in Canada affected their thermal environments to a much greater extent than the practices of people living in traditional homes with central heating who were largely uninvolved in the process of making warmth in their houses. The situation is similar concerning heat exposure. People who live in air-conditioned spaces or in 'perfect' thermal conditions, might not even notice the temperature and heat, therefore not reflecting in any way on their body and their thermoception (De Vet and Head, 2020; Bosca, 2023). While people who get too hot – as we show below – develop and maintain many socio-material adjustments to react to and change their thermoception. As Shove et al. (2014) demonstrate, focusing on materiality enables grasping the intangible aspects of thermal comfort and heat (see also Kobi, 2023).

While Vannini et al. (2014) studied thermoception as socio-material activities and assemblages, Allen-Collinson (2018) explored thermoception during physical activity as a specific 'temperature work', much as 'weather work' (see Ingold, 2010; Vannini et al., 2012). Allen-Collinson et al. (2019) conceptualised 'temperature work' as the process of somatic learning and socialisation into bodily ways of knowing, interpreting, and sense-making (see also Allen-Collinson and Owton, 2015). They pointed out that temperature work involves learning the skills of thermoception and thermoregulation and enduring levels of temperature-related discomfort and unease. It is a physical and cultural process that shapes how heat and cold are felt and experienced.

Studying individual heat exposure through the combination of qualitative research and sensors' data is quite rare, but not non-existent (e.g., Kuras et al., 2015). The most common way of incorporating individual perspectives is through a survey (e.g., Kuras et al., 2015; Hass and Ellis, 2019; Kownacki et al. (2019); Esplin et al., 2019), but the survey is often an insufficient tool to understand individual differences. Moreover, studies focused on heat exposure are more likely to focus only on the sensors' measurements (Bernhard et al., 2015), accounting mainly for the type of activity participants engaged in, not their perception or experience.

Conceptual approach

To account for individual diversity and to get a more holistic understanding of individual heat exposure, we need to draw on different kinds of knowledges. IPCC reports (Pörtner et al., 2022) and other studies on climate change have already demonstrated the need for building on scientific and local knowledges when tackling climate change problems, such as increasing heat (e.g., Gagnon, Berteaux (2009); Bhaskar et al., 2010; Satorras et al. (2020)). As Robles-Piñeros et al. (2020) show, it is possible to analyse the complex relations between different kinds of knowledge as they co-produce each other, without reducing them to simple integration or complete crash. We see the value of our research in "making a diversity of perspectives visible by amplifying the expertise of others" (Maas et al., 2022: 8) and contributing to more co-productive practices in research and in science-policy engagement.

We treat the embodied knowledge about heat of research participants as equally important to the knowledge gathered through the sensors about the thermal environments of their flats and the knowledge from weather stations about urban temperature. We recognise how complex the concepts of temperature (Chang, 2004; Schwartz, 2017) and measurement (Crosby, 1997), especially of physiology (Gould, 1996), are in social sciences, but we do not focus on deconstructing them. Rather by juxtaposing the different sets of quantitative and qualitative data, we look at the convergences and divergences between them (Nightingale, 2016) to co-produce new knowledge on individual urban heat exposure.

Methodology

This article is based on interdisciplinary research conducted by anthropologists and environmental physicists. The complexity of the problem of individual heat exposure requires not only single methods use, but rather their integration (Gutterman et al., 2020; Brennan et al., 2021). What we propose is a combination of ethnographic data with physical measurements that enables grasping adaptive processes and individual differences with a particular level of detail.

The two case study cities, Madrid and Warsaw, are both large capital cities. Madrid, situated in the centre of Spain, with a continental Mediterranean climate, is known for its large and diverse population with metropolitan area of 604.31 km^2 and near 6.7 million inhabitants (INE, 2022). Warsaw, with a humid, continental climate is in the east-central Poland and covers an area of 517.24 km^2, with 1.8 million residents (GUS, 2022). Both cities are affected by the Urban Heat Island effect (see e.g., López Moreno et al. (2015) for Madrid and Gawuc et al., 2020 for Warsaw). This means that inner cities have significantly higher temperatures than their rural surroundings due to human activities and modifications to the landscape (Rizwan et al., 2008), which affects people's health (e.g., Tomlinson et al., 2011). People's experiences and sensor readings are, of course, not comparable for Warsaw and Madrid. Due to the climate and weather differences, what feels like an extremely hot day in Warsaw might be a typical summer day in Madrid. Therefore, we do not compare the data for Warsaw and Madrid, but rather analyse how people feel the heat in each city.

The ethnographic research included 10 participants from each city, all above 65 years old, diversified in terms of gender, socio-economic situation, and geographic location. The researchers who conducted fieldwork, two authors of this article, were fluent in Spanish and Polish respectively. Over two consecutive summers, in 2021 and 2022, they met with the participants bi-weekly, recording interviews, conducting more informal conversations and participant observation. The research focused on people's life histories, health, everyday routines and how they were affected by heat, adaptation practices. Researchers also accompanied participants on walks and other daily activities. The participants'

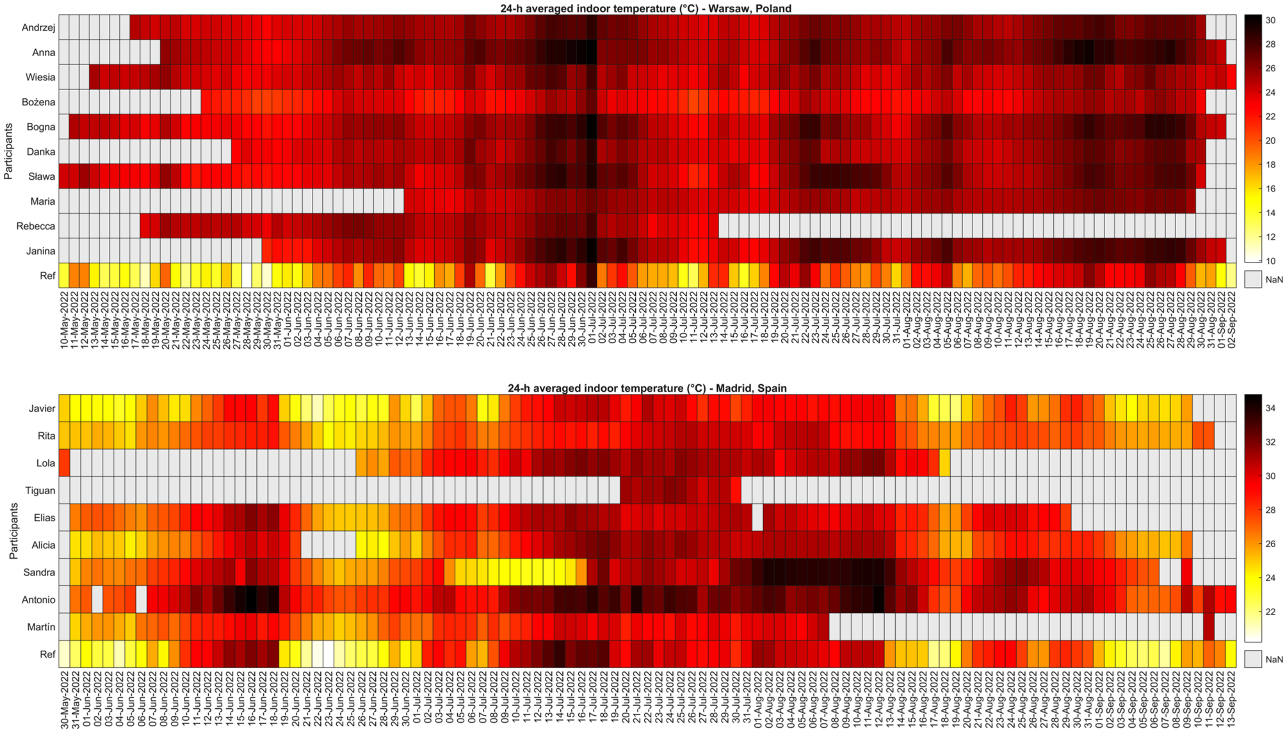

Fig. 1 Visualising temperature patterns: 24-h averaged daily heat map reveals interior temperature intensity. Darker shades indicate higher temperatures. Days with less than 75% sensor data coverage are removed (indicated with light grey).

names have been pseudonymised, and the quotes have been translated from Spanish and Polish by the authors.

While research with the sensors is often supplemented with a small social science component – usually interviews or surveys (e.g., Hass and Ellis, 2019) – we changed the emphasis in our project, and sensors supplemented the ethnographic study. The research with the sensors conducted in 2021 was treated as a pilot study during which both researchers and research participants got used to the sensors while other qualitative methods were implemented. In 2022, we recorded (every 10 min) the air temperature in our participants' homes using Kestrel D2 sensors (Warsaw: 10 May – 29 Aug; Madrid: 30 May – 29 Aug). We downloaded recorded data from the sensors and removed the outliers, defined as recorded temperatures exceeding three standard deviations from the mean. The increasing prevalence of wearable sensors does contribute to a certain degree of ecological validity through bridging the gap between controlled laboratory conditions and the dynamic, diverse environments in which people live.

To compare the sensors' measurements against reference meteorological measurements, we gathered official air temperature data from Okęcie and Barajas stations in Warsaw and Madrid, respectively. The data were available at 20 min intervals, and we calculated the hourly averages.

Moreover, the participants filled out daily thermo-diaries as a participatory research tool to combine the sensor temperature readings and the ethnography. Each hour they were supposed to mark on a five-point scale whether they felt very cold – cold – neutral/normal – hot – very hot. This scale reflects the standardised thermal comfort scale; however, we could not control participants' subjective interpretation of the scale nor their changes in qualifying their thermal experiences over time. The thermo-diaries were then digitalized and juxtaposed with the sensors' readings (Fig. 3 below).

The innovative methodology combining sensors and ethnography required special sample size, that enabled us to highlight the uniqueness of each individual experience. The focus on diversity and uniqueness reveals the different ways in which people interpret, understand and embody temperature, but also how differently they interact with the city, their homes, their family and friends and how they sense and cope with the heat in varied ways. When setting out to understand how heat affects vulnerable populations, all these differences matter. The participants' experiences cannot be generalised, but the unique methodology we use, combining physics and ethnography, is replicable. What we obtain using these methods is a more complex understanding of the relationship between the temperature of the environment, individual interpretation of it and reaction to those through individual adjustments. These observations could have not been obtained through a survey as they required researchers' long-term knowledge of the participants and their activities, so that we could trace back the temperature readings to people's routines and their self-reporting in thermo-diaries, analysing in detail how their subjective experience matched or not their temperature readings.

This article offers an innovative methodological approach that equally validates two different sets of data: the embodied knowledge of research participants and the sensors' knowledge about the temperature, demonstrating how they co-produce a more holistic understanding of individual heat exposure.

Findings: understanding older adults' thermoception

Within one city, people experience very different thermal environments. Fig. 1 (below) shows each participant's average daily temperature readings for the summer of 2022. It shows the differences and fluctuations in individual sensor readings over the summer in relation to each other and to the meteorological reference stations in both cities (the last line of both graphs).

Figure 1 shows that people's homes generally get hotter than reference stations indicate. Most of the flats in Warsaw were substantially hotter than the temperatures indicated by the reference stations. Similarly, in Madrid, participants had relatively hotter experiences in their homes than reported by the reference

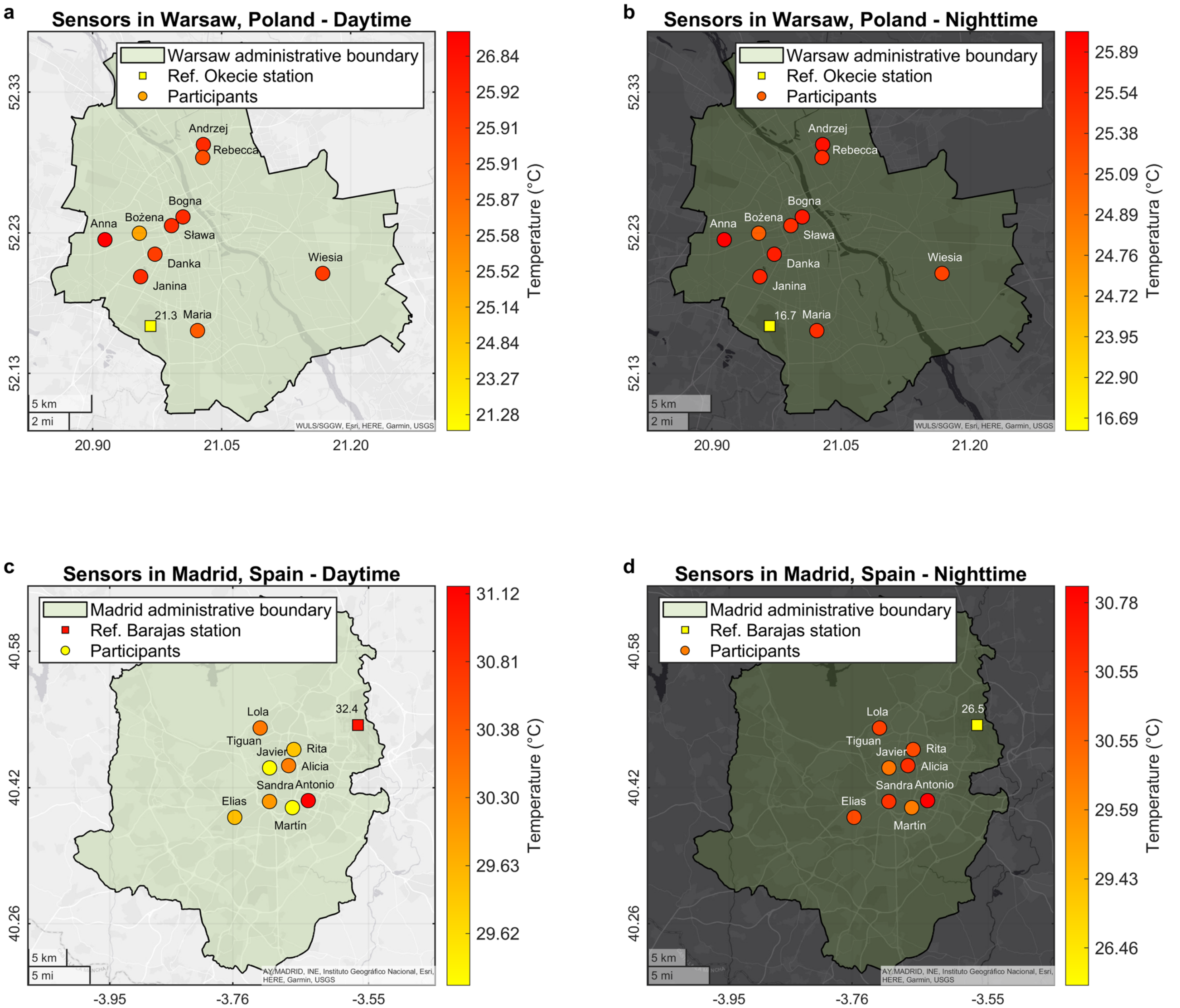

Fig. 2 Spatial distribution of the daytime and nighttime mean temperature inside the participants' homes. a, b Daytime and nighttime mean temperature recorded by sensors in Warsaw. **c, d** Daytime and nighttime mean temperature recorded by sensors in Madrid. Darker shades indicate higher temperatures. The square represents the Okecie and Barajas reference metrological stations' average temperature in the corresponding hours. Only the hours with data availability from all sensors are used for averaging.

station, a difference accentuated for those living in the southern part of the city, Elias, Sandra, Antonio and Martín.

Figure 2 also maps each sensor with its average temperature readings over the summer in contrast to the reference station. It shows the variability between night and day and the spatial distribution of participants in both cities in comparison to the reference station. This is relevant because the reference station values in Warsaw are the only ones that are used to evaluate and issue heatwave alerts. In Madrid, the values obtained in Barajas are placed in contrast with other reference stations across the city, but these are always outdoors and in open spaces. Since the official advice to prevent the effects of heat is to stay at home, highlighting the discrepancies between people's indoor thermal environments and the reference values is necessary to understand the actual level of individual heat exposure. As Fig. 2 shows, the average temperatures in participants' homes are generally lower than the reference station during the day, while considerably higher at night.

Although our study sample does not allow us to confirm the statistical significance of these findings from a physics perspective, through our ethnography we are able to confirm these findings by observing participants' experiences over time. For instance, closing themselves at home during the day and going for night walks was common among participants, reflecting their knowledge about urban thermal environments. We consider this knowledge to be sensorial (see e.g., Ong, 2012; Lara, 2015; McNarry et al., 2021; Kantor, 2019; Royston, 2014; Starosielski, 2019, 2021). However, as Vannini et al. (2014), Shove et al. (2014) and Kobi (2023) demonstrate, to access the intangible aspects of thermal comfort, we need to focus on the tangible adjustments and processes people engage in based on their sensorial experiences. The following subsections will focus on the specific socio-material and socio-temporal adjustments participants made in response to heat exposure. We discuss these as an entry point to the sensorial and somatic experiences of heat, which at the same time explain some of the trends in the temperature graphs.

Socio-material adjustments. The adaptation practices and daily routines people engage in during the day and night to cope with heat in their apartments impact the temperature experienced in their dwellings. That is, people continuously adjust their thermal environments and their bodies based on their thermoception. And they do this through what we call socio-material adjustments.

66-year-old Javier, who lives in Madrid, does not have A/C, but opens his windows below the canopy, creating a current between the inner patio and the terrace, supported by the ceiling fan. In contrast, Martín's (68) windows are protected from direct sunlight by the tree canopy, but he has to use fans and A/C because he cannot open his window due to the noise until late at night in the square. While both Martín and Javier are very aware of the need to close the blinds and windows during the day, for Javier ventilating at night is an elaborate process to move the black-out theatre curtains that cover his windows and to water the terrace and even the wall of the house to create some freshness and keep the plants alive. Martín, unable to do much, repeatedly complained, "I cannot open the windows until the party is over at 3 am; I take a shower on the patio sometimes, but not being able to open the window and let the fresh air in is terrible".

In Warsaw, the practice of opening windows at night was also very common. However, similarly to the situation in Madrid, a few participants complained about the noise which prevents them from ventilating their flats. 68-year-old Sława, for instance, mentioned traffic noise which prevented her from opening windows at night, even though she would have preferred to do so. Moreover, her studio apartment is oriented to east and has only light curtains so there is nowhere to escape the sun radiation.

People's location, their proximity to the centres of the Urban Heat Island (UHI), water and greenery, their building materials – but also the noise outside of their windows – shape their thermal environments, leading to different levels of heat exposure throughout the day. Two people with the highest average temperature in Fig. 2, in Warsaw Anna (73) and in Madrid Antonio (86), live in top-floor apartments, showing that the level of solar exposure of the roof has an impact on the indoor temperature participants experienced (see Vandentorren et al., 2006). In contrast, the people with the lowest average temperature in Fig. 2, in Warsaw Bożena (91), and in Madrid Javier (66) and Martín (68), are the three participants most committed to their routine activities of keeping the house ventilated at night and closing windows and curtains during the day to prevent solar radiation. This demonstrates that individual material adaptation practices have an effect both on people's thermoception and on the actual temperature in the flat. Yet, as shown in the comparison between Javier and Martín above, the means through which a person can intervene in their thermal environment is affected by the built conditions of their dwellings, the possibilities of natural ventilation and the availability of cooling devices.

The participants not only lived in varied material conditions, but they also reacted very differently to heat and had different ways of interpreting comfort. This diversity of experience is not easily visible in their sensors' readings. For instance, 86-year-old Elias from Madrid only turned on the A/C for short periods of time due to the high electricity costs. "I turn it on for 10 minutes and then I move the fresh air with the fan" he said. While 71-year-old Rita used the A/C and fans in all rooms without restrictions, "I don't use it much, but I turn it on to eat or to read a book calmly, and then I cannot sleep without the fan". Yet, the flats of both participants show similar summer and daily temperature averages. This reveals that the adaptation strategies might not change much in terms of 'objective' temperature measurements, but change people's thermoception, sometimes making them feel less hot even when the temperature does not in fact go down.

In other cases, when comparing Antonio's and Sandra's sensors' readings, we can see a mild impact of the use of A/C. Both Antonio and Sandra have A/Cs at home and live in top-floor apartments without canopy coverage. But Sandra used it "to have dinner and then when I am watching TV", while Antonio said, "I use it very little, it's the price, but also now with Covid, when you have it on, you are spreading the virus". Antonio built on his resilience, having experienced a harsh and austere childhood, to withstand longer without turning on the A/C. Sandra, had an equally harsh childhood and had vivid memories of the intense heat she experienced. However, she was not so intensely attached to an austere livelihood. "We need to save energy, but from time to time, to freshen up, the A/C is needed" she claimed. Sandra used the A/C more than Antonio, a difference that can be perceived in the daytime averages in Fig. 2.

The significance of this difference lies in the diverse justifications for people's socio-material adjustments. Despite similar backgrounds of austerity and living conditions participants exhibit different approaches to devices like A/C, based on their thermoception. Antonio's fight to keep the A/C off often led him to periods of dizziness and confusion due to the heat, but he interpreted these as isolated events and undermined their importance. Sandra, contrary to Antonio, was very aware of her thermal needs and the headaches and drowsiness she experiences after prolonged heat exposure. While she had other methods to cope with daytime heat, such as creating air currents and using a water spray on her skin, for dinner she turned on the A/C to cool down her body temperature and the accumulated heat in her apartment. The mild difference of temperature reading between these cases encompasses an array of cultural justifications and the use of material adjustments that lead Sandra to attain thermal comfort and put Antonio's health at risk.

People's individual heat experience, their thermal environment and thermoception, and their material adaptation practices, are shaped by their socio-economic situation and their financial vulnerability, as was the case for Elias and Antonio (see e.g., Seebaß, 2017). Combining the sensors' data with the ethnographic data allows us to understand why people with A/C might have varied flat temperatures and different experiences of heat, as they are shaped by their socio-economic status and material adjustments.

The materiality of the city, neighbourhoods and flats shapes the heat and how people feel it. We mentioned already the influence of living on the top floor (e.g., Vandentorren et al., 2006). Another interesting example of how materiality shapes thermoception is the case of 88-year-old Wiesia. She lives with her husband, Mirek, in a suburban area of Warsaw surrounded by forests, which makes it, in theory, less susceptible to overheating. Moreover, their flat is in a new building constructed in 2020, which makes it subject to the latest thermal regulations (Zielonko-Jung, 2021). Yet, the modern design with massive glass walls all over their living room enabled sun radiation inside their apartment, as can be seen in Wiesia's sensors' readings, with an average comparable to other participants. Wiesia and Mirek further suffered from heat, because they could not spend time outside as much as they wished and used to some time ago. They could not make any use of the forest nearby, even if seemingly close to their flat, they were too far for them to walk, and there were no benches or places to rest on the way, which was especially problematic during heat. In Madrid, Antonio, Alicia, and Lola, with comparatively higher daily averages in Fig. 1, especially in the periods of intense heat, all lived in apartment buildings in Madrid's periphery constructed with poor materials in the 1970s housing boom, before the thermal regulations were issued (Torrego Gómez (2021)). Also, the difference in readings of Javier, Sandra, and Martín, all living in old, refurbished buildings

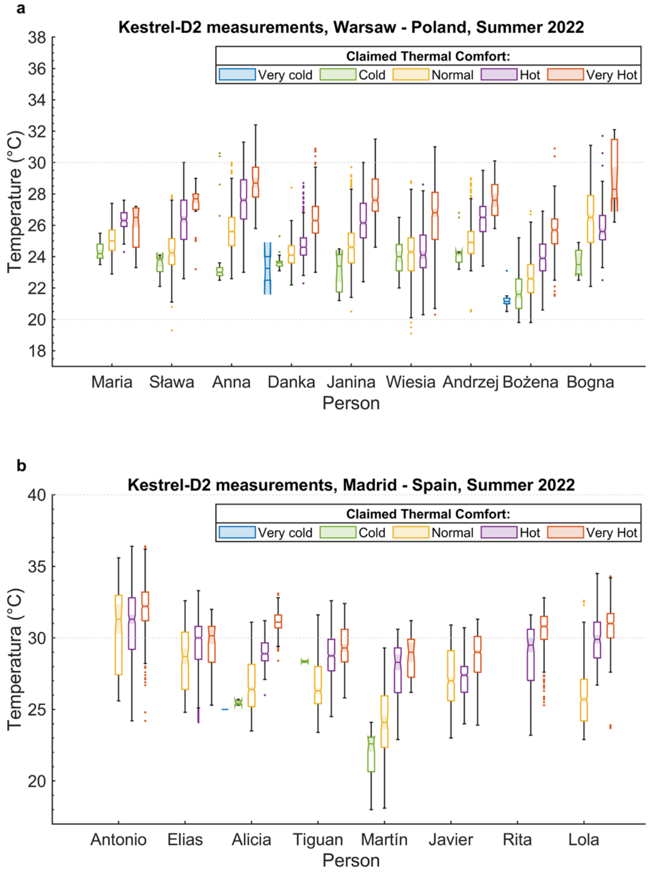

Fig. 3 Temperature statics inside the participants' homes against the claimed thermal comfort level by participants in thermoception diaries. **a** Sensor measurements in Warsaw. **b** Sensor measurements in Madrid. The colour of each box represents the comfort level. Only the hours with thermoception diaries data from all participants are used. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Whiskers extend to the most extreme data points not considered outliers, and the dots indicate outliers. Outliers are defined as those measurements that exceed $q3 + w \times (q3 - q1)$ or fall below $q1 - w \times (q3 - q1)$, where w is the multiplier Whisker (3 here), and q1 and q3 are the 25th and 75th percentiles of the sample data, respectively.

with thick walls, can be explained by the different material contexts in which they live.

The way in which individual participants engaged with their thermal environments has particular social justifications, based on experiences of austerity, illnesses and cultural norms. It is important to highlight what materiality does to our thermoception, because it does not only physically change the temperature, but also leads to specific relations with ventilation and cooling strategies that further change thermal environment (e.g., Shove et al., 2014; Kobe, 2023). This, however, also changes over time. Figure 3 demonstrates what participants marked in their thermo-diaries in the context of sensor temperature readings.

Socio-temporal adjustments. As mentioned in the Methodology section, the participants filled out thermo-diaries, annotating their perceived temperature and adaptation strategies on an hourly basis. Figure 3 compares the distribution (median, lower quartile, and upper quartile) at which the participants reported each value of the thermal scale (too cold, cold, neutral, hot, too hot) compared to the temperature of their sensor readings. Through Fig. 3 we see that each participant had a different range of temperatures at which they felt cold, neutral, or hot. The same temperature felt neutral for one person and hot or very hot for the others. From the graph, we can also understand that there is no clear distinction between what temperature feels, for example, hot and neutral for one person. Sometimes these ranges of temperature overlap, demonstrating how complex thermoception is and that it cannot be reduced solely to temperature.

For 77-year-old Maria from Warsaw, the 'too hot' sensation contains both 'hot' and 'neutral' ranges of experience. Also, there is a relatively small temperature difference of a few degrees Celsius between the sensations of 'cold' (21.5–25.5 °C) and 'too hot' (23.3–27.2 °C). During hot weather, she had to sleep during the day and resign from regular activities, but at the same time, she often caught colds – due to the air currents she was creating during the hot days. She said she liked summers and warm temperatures, which may explain why sometimes she marked the same temperature as neutral and too hot. For her, the duration of a heat event was crucial, "the heat above 30 degrees can be troublesome when it lasts a few days in a row. But when it's only one day, you can ignore it because nothing will heat up so fast, not the apartment, not the neighbourhood", she said. When she went for a trip outside the city, she also reported she did not experience heat, even though she knew it was hot by looking at the thermometer. Her perception of the same temperature varied depending on how long it lasted, as well as on her mental and body disposition. For instance, when she was ill, she experienced the same temperature as much hotter. The focus on temporality enables grasping how the experience of heat changes over time. 70-year-old Alicia from Madrid explained,

> It is not the same thing, the heat we experienced in May compared to June, despite having roughly the same air temperatures, because the body gets accustomed. For me this is a reality. I experience a bad time in the early days of hot or cold weather periods. Then the body stabilises.

The temperature range perceived as too hot by one participant may be perceived as hot or neutral by the same participant at a different point in the summer in a unique pattern different also from other participants. For instance, those participants with the highest average flat temperature, Anna in Warsaw and Antonio in Madrid, have temperature ranges in which they feel too hot that are higher than the rest. Similarly, we see that those persons with the lowest average temperature in Fig. 3, in Warsaw Bożena and in Madrid Javier, feel colder than others, even experiencing periods of cold. Yet, Martín in Madrid, with comparatively low average temperature readings, indicated ranges of thermal (dis) comfort higher than Bożena and Javier and comparable to the average of Madrid's participants. These differences in thermoception could manifest also through clothing. While Anna in Warsaw and Rita in Madrid dressed in breathable fabrics, without much relief for Rita, who reported being hot and too hot all summer long; Bożena in Warsaw and Alicia in Madrid, wore socks all the summer, and Bożena wore a light sweater even during a heatwave.

Martín concluded that these differences in thermoception did not stem from people's different living conditions or adaptation strategies, but from different bodily predispositions to heat and the ways in which we individually cope with heat stress. In his case this included going to the park.

> When I can, in the afternoon, I go up to the park to feel the air currents to cool down the sweat on my skin; this way, I feel more energy to go back home because the heat for me is like a weight that produces a physical limitation that I translate into my legs directly. I also feel the heat on my

> head, my lungs, and below the neck, especially at night when I can't open the windows; it's suffocating.

While he made use of every available adaptation strategy and was conscious of their importance, he saw how the accumulation of the lack of fresh air and the need to resort to cooling devices to entertain everyday life suffocated him. As his mood changed, due to his inability to tolerate heat, so did his perception of the heat, reflected in the overlapping ranges of temperature at which he felt normal, hot, or too hot (Fig. 3).

People's thermoception is not only shaped by the environment, and physical bodily reactions, but also by their mood (see Wang et al., 2018). The emotional state while exposed to heat matters, and while some extreme heat experiences might be pleasurable – for instance holidays by the sea – other mild heat experiences can result in discomfort. Temporality is important as heat discomfort becomes distress, challenging participants ability to protect themselves from the heat. Alicia and Martín, who were both shocked by the early summer heat in Madrid, described discomfort at the onset of the summer, which as the heat period prolonged, became emotionally challenging for them to overcome.

This was different for Elias, who explained the heat peaks corresponded to the days of the neighbourhood festival and overseeing the barbeque. Elias embraced the heat as part of a seasonal pattern, accompanied by certain cultural festivities and traditions, leading him to consider this a positive experience. All participants in Madrid experienced an unusually early heatwave in 2022. However, in Elias' case, he did not only engage his body with the heatwave, but also with the heat of the barbeque, the heat of the people in his neighbourhood festival, and overall excitement for the start of the summer. While Elias soon after also became disenchanted with the heat and stopped all positive remarks in his diary, these insights show the importance of the social context for understanding individual heat exposure. Moreover, it demonstrates the importance of feeling 'in control' over one's environment. Participants relied on their embodied knowledge to cope with heat and modify the degree of stress provided by the increase in temperature.

The ethnographic research demonstrates that participants have diverse ways of understanding and expressing heat exposure. Some expressed it through temperature, others through bodily sensations, and others related to their memories and personal background. In contrast to the sensitivity of Martín, 84 years old Andrzej from Warsaw, from the beginning of our study kept repeating he did not feel nor experience temperature. The idea of reporting how he felt depending on the weather was strange to him. Ignoring weather conditions was part of his strong masculine identity. He said,

> I'm kind of thick-skinned, on purpose. [I don't feel if] it's too hot or too cold. I'm not so sensitive. I often laugh 'it's hot, so what'. Until noon it is fine; you can stand the heat here. (…) I simply do not feel [the heat]. Of course, you need to dress in lighter clothes, etc., so I don't wear an undershirt, for example, but I'm not like others who are like, 'I can't breathe'.

Even though Andrzej claimed he did not notice the heat, he adjusted his clothing to the temperatures, but only up to some point. He would not wear shorts, as it is considered by many older people in Poland as not appropriate for an older person. Similarly, Antonio in Madrid also did not wear shorts in the street. Yet, while Antonio reported being too hot throughout the summer, Andrzej only reported being too hot for more than three consecutive days at the beginning of the summer. Throughout July and August, he did not report a single hour of being 'too hot'. He was an extreme example since, according to other participants and meteorological data, there were at least two or three heatwaves during the summer of 2022 in Warsaw. Similarly, 78-years-old Bogna, who has diabetes and many other chronic diseases, suffers a lot during hot weather. She sweats, has difficulties with movement and breathing and reported thermal discomfort to the researcher, but she barely never marked she was too hot in the thermo-diary.

Andrzej and Bogna seem to indicate they are too hot during the highest temperatures of all participants – for Andrzej it was 25.8 °C and for Bogna 26.2 °C, whereas for Bożena 'too hot' started already when it was 21.5 °C (see Fig. 3). It is possible that they modified their ways of interpreting the scale through accumulated experience or engaged in 'temperature work' during a period of discomfort while getting accustomed to the heat. For Andrzej, Bogna but also Alicia, Anna, Sława and Antonio, longer periods of hot weather resulted in some kind of physical and mental adaptation. As a result, they started to feel 'too hot' at higher and higher temperatures throughout the summer. The change was accumulated in their bodies and shaped by the initial days of thermal discomfort. Others, however, react differently. In contrast, for Maria the longer periods of heat resulted in lower levels of resistance toward high temperatures.

In Warsaw, Anna (73), whose sensor showed higher flat temperature readings over the summer, reported fewer "too hot" hours than Bożena (91). Anna did not have curtains or fans, and while she complained about the heat, she did not engage in any adaptation measures until the end of the summer, when she bought a curtain. Bożena, more sensitive to hot temperatures, kept her apartment cooler through long-term adaptation practices, like covering her windows with inner curtains and pieces of plywood, to maintain thermal comfort. Yet, even though Anna's sensor readings showed her apartment was the hottest among participants, and the range of temperature in which she reported being too hot is higher than that of Bożena, Fig. 3 shows that Bożena was overall more aware of the heat and of her efforts to withstand it. She might have been more vulnerable, but we see that vulnerability is not only linked to exposure, but also to our ability to adjust and our perception of how well or not we adapt over time.

The temperature inside the apartments is shaped not only by the houses' materiality but also by people's thermoception. It is an interdependent relationship. Those participants who were not reliant on cooling devices, but actively engaged with non-energy dependent adaptation strategies, such as Bożena in Warsaw and Javier and Alicia in Madrid, have more differentiated ranges of temperature at which they feel 'hot' or 'too hot'. This is because they were more exposed and more engaged in maintaining indoor freshness without the use of cooling devices. Beyond covering windows and ventilation practices, the participants also sprinkled or sprayed water on and around their bodies, took chilly showers, refreshed their bodies with ice, moisturised their skin, and slept with wet towels. Alicia argued,

> During the hours of intense heat, I just sit, sometimes with my eyes closed, waiting for time to pass by. When it is too much, I sprinkle some water on my wrists and the body calms down a bit as I return to waiting.

Therefore, participants actively invested their bodily and mental energy to perform the temperature work. These adjustments cannot be seen in the sensors' readings, and we cannot claim they changed the participants' environments, but they offered a moment of relief and refreshment that in the case of Sława in Warsaw and Alicia in Madrid, was fundamental to get by through the day.

Discussion

While many studies focus on the differences in thermoception and heat exposure analysed separately (e.g., Bernhard et al., 2015; Kuras et al., 2015; Kántor et al., 2016; Beckman et al., 2021), we analyse the relationship between the two on a small scale. This provides a new understanding of individual heat exposure and how it is shaped by people's behaviour. Individual heat exposure stems from an interplay between a thermal environment and people's adjustments. As we know from previous studies, people are capable of changing their thermoception through numerous practices (see Vanini et al., 2012; Vanini et al., 2014; Kobi, 2023). In our research, we were able to closely study such adjustments and show that people's thermoception may change even though the temperature remains the same. Through thermoception, participants not only felt their surroundings but also engaged with the materials available to create and modify air currents and their felt temperature. This demonstrates the importance of people's embodied knowledge and agency in shaping their individual heat exposure.

The focus on social, material and temporal adjustments shows how older adults modified their thermal environments based on embodied knowledge. When participants engaged in adaptation practices, such as ventilating, covering their windows, but also showering or putting a fan on, the temperature in the room did not necessarily change (at least mean temp), even though their thermoception did due to their engagement with their bodies and surroundings. This engagement can lead to personal frustration when it does not produce the refreshment desired, as was the case of Martín in Madrid and Anna from Warsaw. It can also lead to feeling less hot when people manage to modify their environment (but not necessarily its temperature) or when they have a mental and physical predisposition to withstand heat, as was the case of Javier, Alicia, Sława, and Andrzej.

The existing studies on individual heat exposure rarely account for people's stories and daily routines. For instance, if we know their apartments we do so only via questionnaires, not the everyday practices people engage with. Similarly with cooling strategies, if they are brought into the picture, they are rarely analysed in the context of people's routines, emotions and perceptions. While our low sample does not allow to generalise the findings, what we were able to gather from ethnographic research shows that there are diverse social and behavioural factors influencing how participants engage with materials to change their environments. These factors include financial constraints, physical vulnerability and health issues, personal experience, and social and cultural norms (see e.g., Seebaß, 2017; Okyere and Lin, 2023). Drawing on in-depth ethnographic testimonies we show how two participants, Sandra and Antonio, with similar family stories and the socio-economic situation may differently interpret their thermal comfort, which would not be possible to trace with other methods.

Comparing and juxtaposing different data sets gathered through qualitative and quantitative methods enabled us to look at the convergences and divergences between them (Nightingale, 2016). We found an important divergence between participants' heat experiences based on thermo-diaries and sensor temperature readings (Fig. 3). From ethnography we know the same temperature in different moments felt differently to participants. The nuances in how participants experienced heat and accounted for it, the different range of temperatures at which they felt 'neutral' or 'too hot' contrast with the sensors' temperature readings. Due to the longitudinal relationship with the participants, we know how their perception of a given temperature changed over the summer. Andrzej from Warsaw noticed only a few days of heat, although he was exposed to similar temperatures as Bogna who was more susceptible to heat. For Anna, the heat did not matter if it lasted one or two days but was burdensome when lasting longer. And Alicia from Madrid became used to the temperatures over the summer.

Another divergence is related to the use of A/C, which only participants in Madrid had. We found unclear links between the use of A/C or natural ventilation and a decrease in participants' temperature readings. The sensors did not pick up any significant changes when participants in Madrid used A/C. But such adaptation practices affected how people felt and perceived the heat.

There was also significant difference in temperatures across the city, as Fig. 2 shows. Participants' thermal environments were affected by their building location and materials, proximity to water and greenery, the location of their flat. However, only ethnographic data allows us to see the nuances between participants as well as to truly comprehend their vulnerability. For instance, if we accounted just for the general geographical data about Wiesia and Mirek's home, we would assume it should be heat-resistant as it was built according to the newest regulations and was based in the outskirts of the city, surrounded by greenery. But only studying their daily routines and needs, we know they actually suffered from heat.

By comparing people's social, material and temporal adjustments with temperature readings we can see how thermoception is configured, revealing the importance of this embodied knowledge when studying the effect of heat on the population. Vannini et al. (2014) demonstrated in regard to cold weather, that people who lived in off-grid houses and had to routinely and daily adjust their thermal environment, were much more aware of the temperature and their surroundings. Our research also shows that engaging in various adaptation practices to urban heat affects people's thermoception. Those participants who were more active in shaping their thermal environment, and who displayed more agency in reacting to heat, were also more sensitive to the hot weather. Perhaps they were more active exactly because they were more sensitive to heat. Engaging in mental or material adjustments, even if not affecting the temperatures in their dwellings, had effects on how they felt.

Taking that into account and recognising the role of thermoception in understanding individual heat exposure can affect the city-wide adaptation systems. Heat warnings in Warsaw and Madrid are universal for a whole city and based on the temperature measured in outdoor meteorological stations, usually not in high population density or UHI areas. Warning systems could benefit from further research that recognises diversity in thermoception among vulnerable groups and understands the role of people's bodies and their actions in the transformation of their thermal environments. For instance, both the data from the sensors and thermo-diaries show that Warsaw had a period between the 7th and 12th of June 2022 when participants experienced more heat, which was not recognised by the official heatwave warnings. Also, in Madrid, we observed that participants had a relatively hotter experience during the May heatwave than during other heatwaves throughout the summer, even though the warning system only issued a level 1 alert (out of 3). In this case a warning system that considers thermoception would be more accurate and closer to the lived experiences of those who are most vulnerable to heat exposure.

Looking for ways to incorporate the focus on individual and subjective thermoception into city-wide adaptation systems requires further interdisciplinary research. Our approach combines ethnography and physical measurements on a very small scale. It would be interesting to consider the possibilities of upscaling and potentially quantifying such an approach (see Mazzone et al., 2021). Moreover, it would be particularly fruitful to account not only for people's social and cultural practices, but also incorporate the focus on biology and physiology when studying thermoception. Such interdisciplinary approaches allow co-producing new knowledge about the diversity of individual heat exposure.

Conclusion

This article emphasises the role of social sciences and qualitative methods in research on individual heat exposure. While extreme heat events are becoming and will continue to be more frequent and intense (Pörtner et al., 2022), there is still limited understanding of how the most vulnerable groups, such as adults above 65 years old, experience and deal with urban heat (Nazarian, Lee (2021); Vargas et al., 2023). This article demonstrates that through an interdisciplinary approach combining quantitative temperature measurements and qualitative accounts of people's experiences, we can better understand how older adults feel and adapt to urban heat. Moreover, by accounting for personal stories and daily adjustments, and by studying people's thermoception, we are able to understand the diversity of individual heat exposure.

Throughout the article we demonstrated how people's individual heat exposure is shaped by their bodies and environments, in an interdependent relationship. Older adults living in Warsaw and Madrid, who participated in our research, lived in very different material and thermal conditions in different parts of the city. They also had very different bodily reactions to urban heat. Their engagement in various mental and material adaptation practices aimed to change their thermal environments – from opening the windows at night, closing the shutters during the day to sprinkling water on their bodies – was based on their embodied knowledge. Those participants who were more conscious of heat and engaged in adaptation practices, felt the effects of their own behaviour. Ethnographic methods combined with quantitative sensors' measurements enabled us to grasp the nuances of these thermal experiences and demonstrate the important role of people's agency and their thermoception in shaping individual heat exposure.

Data availability

The qualitative datasets generated and analysed during the current study are not publicly available to protect participants' anonymity but are available from the corresponding author on reasonable request. The sensor data associated with this study are freely available on Figshare repository https://doi.org/10.6084/m9.figshare.25650306.v1 (Yañez Serrano et al., 2024).

Received: 3 October 2023; Accepted: 22 April 2024;
Published online: 06 May 2024

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Acknowledgements
We would like to thank all research participants for their time and engagement in the project. The article stems from the research project "Embodying Climate Change. Transdisciplinary Research on Urban Overheating" (EmCliC) funded from the EEA grants 2014–2021 under the Basic Research Programme operated by the Polish National Science Centre in cooperation with the Research Council of Norway (grant no 2019/35/J/HS6/03992).

Author contributions
All authors made substantial contributions to the article. The co-authors are listed in alphabetical order. Research design and funding acquisition were performed by Zofia Boni. Conceptualisation of the paper and writing of the first draft were performed by Paloma Yáñez Serrano. Research, data curation and analysis of ethnographic research in Warsaw were performed by Zofia Bieńkowska. Research, data curation, analysis of ethnographic research in Madrid and interdisciplinary analysis were performed by Paloma Yáñez Serrano. The literature review was performed by Zofia Boni. Data curation and policy analysis were performed by Franciszek Chwałczyk. Data curation and analysis on sensors and their statistical analysis (including Figs. 1, 2 and 3) were performed by Amirhossein Hassani. All the authors contributed to the interdisciplinary analysis and discussion, worked on revisions, and read and approved the final version of the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
The research which is the basis of this article received approval from the Ethics Committee for Research Involving Human Participants at Adam Mickiewicz University in Poznań (decision no 6/2020/2021). All the participants, who are pseudonymized in the article, provided written consent and were informed about the possibility to withdraw their consent and participation from the research at any time. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Informed consent
Informed written consent was obtained from all participants.

Additional information
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