How does perceived heat stress differ between urban forms and human vulnerability profiles? – case study Berlin

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Abstract.

Urban areas in all world regions are experiencing increasing heat stress and heat-related risks. While in-depth knowledge exists in terms of the urban heat island effect and increased heat stress in cities in the context of climate change, less is known about how individual heat perceptions and experiences differ between urban forms or with different vulnerability profiles of exposed people. It is crucial to identify and assess differences within cities relating to urban form and social structure, as both need to be considered when designing adaptation plans for heat-related risks. Here, we explore linkages between urban structure types (USTs), heat stress perception and different socioeconomic group's experiences in Berlin using a household survey, statistical and earth observation data. Our approach (1) quantifies perceived heat stress across USTs, considering characteristics such as, age, income, vegetation cover and shadow; (2) characterises social dimensions of UST to enhance it being addressed in climate adaptation; and (3) benefits from the synergistic disciplinary approach of the *urbisphere* project with rich social and physical datasets. Although heat stress exposure is higher in the inner-city ring, we find that a higher percentage of vulnerable groups in the outer city (6 km to 18 km from city centre) where 78% of Berlin's elderly live. We underscore the need for attention in future adaptation plans based on the USTs, human vulnerability profile and adaptive capacities. For example, in densely spaced building blocks 67% of respondents perceived high heat stress and fractions of vegetation and shadow are comparatively very low. The method and findings can inform future adaptation strategies of other cities to consider different profiles of vulnerability and adaptive capacities within and between USTs.

1. Introduction

Globally, all regions are increasingly affected by climate change (IPCC, 2023). Heat stress is a key challenge impacting ~~more as~~ urban citizens, as about 56.2% of the global population lives in urban areas and is projected to increase to 68.4% by 2050 (United Nations, 2022). While human vulnerability is highest and resilience lowest in rapidly growing urban areas in developing countries (Birkmann et al., 2016), heatwaves impact cities globally (e.g., Europe 2003; Schär et al., 2004) highlighting a general need for enhanced resilience. Global increases of near-surface air temperature are projected to be 2°C by 2050 (Rosenzweig et al., 2018) without immediate reduction in GHG emissions (Gallardo et al., 2022). Cities are potentially subject to twice the levels of heat stress as compared to their rural surroundings under all representative concentration pathways (RCP) scenarios by 2050 (Wouters et al., 2017). Compound events are likely with urbanization and frequent extreme climate events resulting in adverse consequences (Babiker et al., 2022). Heat stress impacts urban residents by adding health burdens, notably cardiovascular, respiratory (Augustin et al., 2025), vector-borne disease (e.g., dengue fever and malaria; Song et al., 2016; Li et al., 2015), and can lead to negative impact on self-rated health (Szombathely et al., 2019) and decreasing work productivity (Park et al., 2015). Heat-related mortality, a key climate change risk to human health (Vicedo-Cabrera et al., 2021; Lüthi et al., 2023), is exacerbated in urban areas as global and regional temperature extremes are intensified by the urban heat island effect (Gallardo et al., 2022). Heat risk for individuals depends on exposure, vulnerability and adaptive capacities (Adelekan et al., 2022). Exposure and vulnerability are framed differently (IPCC, 2022), with exposure defined as the presence of something valuable that may be adversely affected by the impacts of a hazard. Whereas vulnerability is 'the propensity or predisposition to be adversely affected' and it encompasses susceptibility to be negatively impacted and inability to cope and adapt to hazards (IPCC, 2022). Exposure to hazards can be reduced through altering urban growth and managing physical hazards, while vulnerability can be reduced by promoting inclusive development and addressing inequality (Adelekan et al., 2022).

Urban and spatial planning primarily focuses on physical urban typologies and phenomena when dealing with climatic risks and adaptation issues (Turek-Hankins et al., 2021; Wendnagel-Beck et al., 2021; Marando et al., 2022), but different levels of human vulnerability and adaptive capacities of residents are insufficiently addressed (Turek-Hankins et al., 2021). Despite susceptible group's coping and adaptive capacity being included in some climate risk assessment frameworks (Willroth et al., 2012; Birkmann et al., 2013; Kunz-Plapp et al., 2015; Feldmeyer et al., 2017; Jamshed et al., 2017; Feldmeyer et al., 2019; Zuhra et al., 2019; Sun et al., 2021, Iqbal et al., 2022), this knowledge is often unconnected in practice (e.g. in climate adaptation plans, Hannemann et al., 2023). Heat adaptation plans implemented with marginalized and vulnerable populations as targets are little published (Eldesoky et al., 2022). Evidence of heat adaptation plans addressing populations living in lower-income neighbourhoods or being homeless are few. Examples include planting vegetation in prioritized vulnerable areas with less access to green spaces (e.g., Aburrá Valley city's Mayor's Office and the Metropolitan Area Medellín Colombia, 2021), creating shady, cool places outdoors (e.g., awnings/tents) for homeless people, and distributing water bottles (e.g., counselling centres and day centres; Bochum Department of Social Affairs, Germany, 2021).'Heat equity' involves, for example, planning a city-wide network of connected cool areas (parks, pools, walkways) in Paris, France ("Cities must protect people from extreme heat", 2021). As socio-demographic and economic aspects of exposed people determines human vulnerability, they are also key when trying to understand and respond to heat related risk in cities. Thus, urban planning responses to climate change need to better account for dynamics and patterns of exposure, vulnerability and adaptive capacities of people.

1.1. Urban form classification – combining urban morphology and heat characteristics

Many studies illustrate impacts of urbanization on heat stress (Stewart and Oke, 2012; Lemonsu et al., 2015; Narocki, 2021; Tollefson, 2021; Tuholske et al., 2021). With greater urbanization both urban heat islands intensity (Stewart et al., 2021) and energy consumption (Voogt and Oke, 2003; Stewart et al., 2021) increase. However, urbanization also plays a pivotal role in reducing the impacts through climate resilient development (Adelekan et al., 2022) through numerous factors (e.g., vegetation, materials, anthropogenic heat flux), with urban morphology being one of the strongest influences on urban heat island intensity (Oke, 1981; Grimmond, 2007; Oke et al., 2017; Gallardo et al., 2022). Tall dense buildings can trap and reradiate longwave radiation, slowing cooling after sunset (cf. rural areas) and reducing windspeed within the urban canopy (Grimmond, 2007; Oke et al., 2017). Building materials store large amounts of heat during the day, providing a large source of energy to be released at night (Grimmond and Oke, 1999; Oke et al., 2017). By contrast, open vegetated areas can cool more rapidly at night, facilitating thermal circulations relative to warmer areas and therefore reducing heat stress. Human activities in domestic, commercial, and industrial areas or traffic-related heat sources act as a source of anthropogenic heat, contributing to local atmospheric warming (Schwingshackl et al., 2024). Understanding the impact of urban form and function are important for a wide range of applications in many sectors (e.g. Barlow et al., 2017), including infrastructure and landscape planning. Form, characterised by many parameters (e.g. sky view factor, vegetation height, floor area ratio and building aspect ratio; Yang et al., 2021; Liu et al., 2023; Hertwig et al. 2025), influences energy exchanges (e.g. Zhou et al., 2011; Oke et al., 2017; Yue et al., 2019; Fenner et al. 2024). These spatial differences are fundamental to creating exposure differences, which combined with disadvantaged urban dwellers can exacerbate vulnerabilities (Adelekan et al., 2022).

To characterise neighbourhoods in a globally comparable way for urban heat island intensity, Stewart and Oke (2012) propose local climate zones (LCZs) that are described by several parameters, including building density, sky view factor and impervious fraction. Given the ease of obtaining many of the parameters from satellite-data (e.g. Mitraka et al., 2015; Zhu et al., 2018; Oliveira et al., 2020) and air temperature observations via crowd-sourcing, many urban climate studies have been undertaken, e.g., in Berlin (Fenner et al., 2017) and elsewhere (Bechtel et al., 2015; Verdonck et al., 2018; Bechtel et al., 2019; Ren et al., 2019; Aslam et al., 2022). Planners are using LCZs quite widely (Klopfer, 2023) with maps for cities becoming globally available (e.g. Demuzere et al., 2022). However, using LCZ maps for climate adaptation planning still requires local expertise (Klopfer, 2023). Additionally, the LCZ classes may not be globally representative, with parts of a city being difficult to classify (Bechtel et al., 2015; Zhu et al., 2018) using the original classes.

City planning departments have combined building metrics (e.g. functional use, number of storeys, building age) to identify urban structure types (USTs) in their regions (Senatsverwaltung für Stadtentwicklung und Umwelt, 2014; Senatsverwaltung für Stadtentwicklung und Wohnen, 2021; LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2014). These can identify inter- and intra-urban variations of both physical and social urban structures (Wendnagel-Beck et al., 2021). In climate change studies, USTs have been linked to climate hazards such as heat stress and are used for climate adaptation planning in some cities (LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2014; Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023). Whilst USTs require expert input and detailed data to be developed (Klopfer, 2023), LCZs are intended to provide 'standard' descriptions of parts of cities so may have greater utility in multi-city large scale applications (Bechtel et al., 2015; Zhu et al., 2018). Nevertheless, both are applicable in a particular city and region, and could be used in city planning and climate adaptation.

1.2. Urban structure type (USTs): considering physical and socio-economic factors to assess cities for climate adaptation

USTs already form an important basis of adaptation plans for heat stress in some German cities, with more being currently developed (Senatsverwaltung für Stadt-ent-wicklung und Umwelt, 2014; LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2014; Downes et al., 2024). For example, Karlsruhe and Berlin consider USTs in their climate adaptation plans and strategies (Senatsverwaltung für Stadtentwicklung und Umwelt, 2014; LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2014). The methodology has three steps, as outlined by Wendnagel-Beck et al. (2021): (1) characterizes cities through USTs, (2) identifyies climate hotspots that require adaptation, and (3) develops adaptation measures for different USTs. Many applications have characterized USTs using only physical indicators (e.g., building age, building height, building use, building geometry, and open space characteristics). In the identification of climate hotspots, sometimes demographic aspects (e.g., elderly, children and population density) are captured, for example, as done in Karlsruhe (LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2014). However, some key socio-economic and behavioural aspects like income, risk perception and experience and willingness to adapt are not investigated fully (Wendnagel-Beck et al., 2021).

USTs are used in urban monitoring; for instance, assessment of peri-urbanization transitions (Downes et al., 2024) and amount of residential greenery (Battisti et al., 2019). Climate assessments using USTs have been undertaken to assess influential factors on land surface temperature (LST). In Berlin, both building height and plan area plus impervious area are identified (Klopfer, 2023), while in the case of Munich the UST distance from the city centre is considered important (Heldens et al., 2013). In Leipzig, indoor and outdoor temperatures are compared using USTs (Franck et al., 2013) and Dresden's guidebook on adapting to climate change uses USTs as an indicator for settlement heat sensitivity (Wende, 2014).

However, most studies using USTs focus on physical structures and lack socio-economic and vulnerable population information (e.g., elderly, low income, and/or otherwise disadvantaged groups). Impacts of heat, heat stress perception of UST dwellers (e.g., detached houses, block development, row houses, large housing estates) and their socio-economic attributes (e.g., age, income) are insufficiently explored and integrated into adaptation strategies, despite this being crucial information for effective people-centred adaptation. Berlin's Urban Development Plan Climate 2.0 (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023) identifies cold air drainage and climate function of open spaces, but less information is available on the population's socio-economic characteristics, heat stress perception, behaviour patterns and adaptation responses. To address these aspects, a household survey (section 2.2) is undertaken in Berlin to explore:

I. Does perceived heat stress change from the centre of the urban region towards the periphery?
II. How does measured thermal comfort correspond to perceived heat stress by residents?
III. How does perceived heat stress differ within a UST and along various USTs?
IV. Are inter- or intra-UST human vulnerability characteristics and adaptive capacity differences significant?
V. How does perceived heat stress differ amongst various socio-economic groups and vulnerability factors?
VI. How can this new knowledge be applied in future climate change adaptation strategies of urban regions?

The ERC *urbisphere* project aims to characterise intra-city variability in a consistent manner globally. To do this, a simple ring structure is developed based on building density and other parameters (Fenner et al. 2024) for Berlin (section 2.1). Here, we capture similarities and differences of perceived heat, socio-economic structure and adaptive capacities across USTs and city rings and explore the correlation between them.

2. Methods

2.1. Berlin study area

Deutscher Wetterdienst and Senatsverwaltung für Stadtentwicklung (2010) found Berlin citizens are experiencing increasing heat stress from rising regional temperatures, intensified by the urban heat island effect, linked to a 1°C increase in mean annual air temperature between 1971 and 2000. Between 1967 and 2008 the average number of tropical nights (nocturnal air temperature > 20°C) increased by five in the inner city (Deutschländer et al., 2010). By 2050, the average number of very hot days (maximum temperature > 30°C) is expected to be 25 annually (Deutschländer et al., 2010). With Berlin's continental climate exacerbating summertime heat, city planning and environmental departments are increasingly keen to enhance their adaptability potential (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023).

TheThe Berlin region has a polycentric city structure, notably with two city centres existing from the east-west separation after World War two period. Following the *urbisphere-Berlin* analysis of campaign analysis of form (building area fraction, vegetation area fraction, and building volume) and function data (population density, anthropogenic heat inffluxes)– identified, an inner city ring (radius 6 km) and an outer (18 km) city rings (Fenner et al., 2024, their Fig. 2) (radius 18 km) are identified. This Our ffirst order analysis premise gives with ring structure is that there are broadly three wo city zones (inner and outer city,), surrounded by a rural) area for . The prothe iposed ring structure for Berlin is defined by an interdisciplinary team (meteorology, remote-sensing and urban/spatial planning) to have a simplified, comparative and replicable approach between cities (Fenner et al. 2024). Central to this is providing a complementary approach between both urban climate and planning studies. In this context, classifications and analysis schemes of different research communities are applied and linked. For our analysis, we split the outer ring at 12 km, giving three urban rings (hereafter A, B1, B2) from inner to outer Berlin (Fig. 1a).

The Senatsverwaltung für Stadtentwicklung und Wohnen (2021) identified 13 residential USTs (Table 1) for Berlin, with some patterns arising from the east-west separation (post-World War II period) when. Berlin had two city centres. To reduce these 13 classes to seven (Fig. 1a, Table 1), we compare We use 5-95th percentile ranges of socio-demographic and physical datasets (e.g., population density, building morphology, number of storeys, building age, green volume, degree of sealing, Table A1) to reduce these 13 classes to seven (Fig. 1a, Table 1) for comparison. In ring A, there is a larger proportion (42%) of dense and close block USTs than in either rings B1 or B2 (Fig. 1b). Block edge developments are also comparatively higher in ring A. In rings B1 and B2 (54% and 75%, respectively), (semi-)detached and terraced houses dominate. In rings A and B1, row development with green landscape strips are also common (13% and 16%, respectively). Whilst large estate development with high-rise buildings occur in all three rings, the proportion decreases with increasing distance from the centre (A: 11%, B1: 10%, B2: 8%).

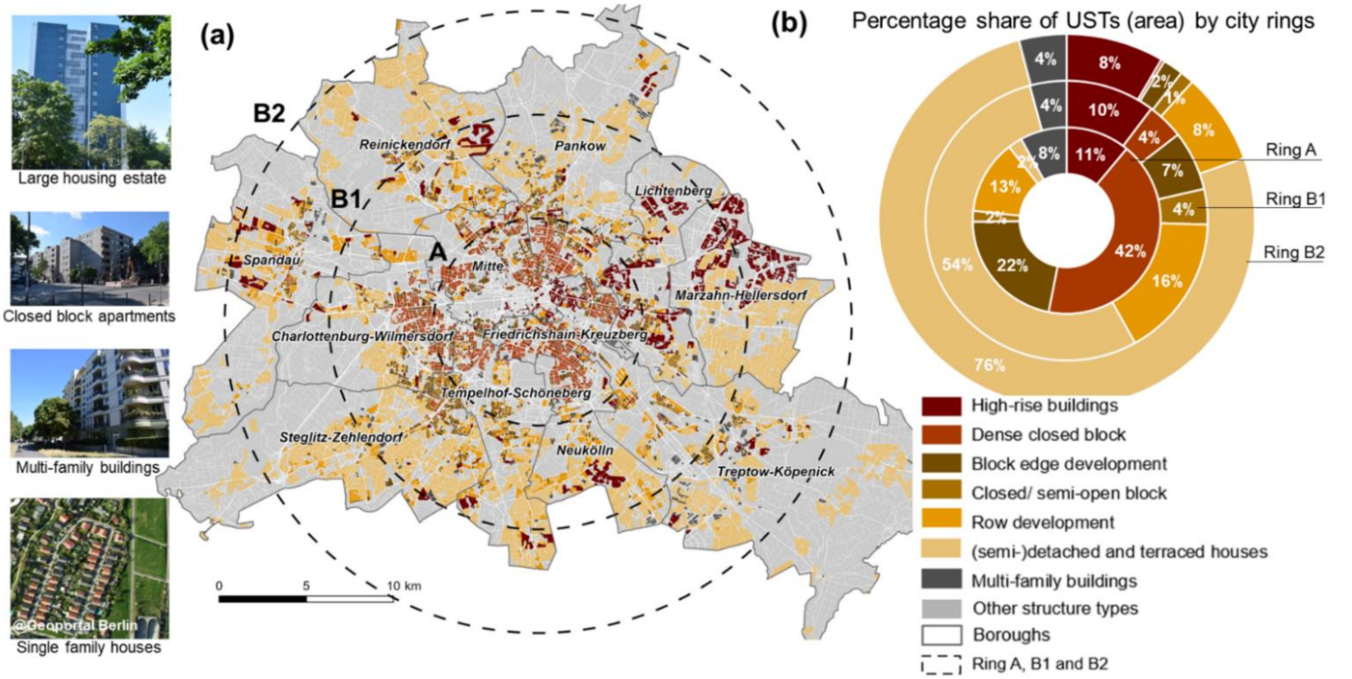


Figure 1. Berlin study area (a) inner (A) and outer (B1, B2) city rings and Senatsverwaltung für Stadtentwicklung und Wohnen (2021) urban structure types (UST, Table 1) with example photos and boroughs labelled, and (b) plan area of USTs (%) in each city ring. (Photo source: Marvin Ravan).

Table 1. Berlin's urban structure types (UST) (Senatsverwaltung für Stadtentwicklung und Wohnen, 2021), new UST classes and short name use. Table A1 gives basis for the new classes.

USTs based on residential form	New Classes	Short name
Large estate with tower high-rise buildings (1960s-1990s), 4-11-storey	Large estate with tower high-rise buildings (1960s–1990s)	High-rise buildings
Dense block development, closed rear courtyard (1870s-1918), 5-6-storey	Dense and closed block (1870s–1918s)	Dense closed block
Closed block development, rear courtyard (1870s-1918), 5-6-storey		
De-cored block-edge development, post-war gap closure (after 1945)	Block edge development (1920s–post war gap closure)	Block edge development
Block-edge development with large quadrangles (1920-1940s), 2-5-storey		
Closed and semi-open block development, decorative and garden courtyard (1870s-1918), 4-storey	Closed and semi-open block development (1870s–1918)	Closed/~~-~~semi-open block
Free row development with landscaped residential greenery (1950s-1970s), 2-6-storey	Row development with landscape green strips (1920–1970s)	Row development
Parallel row buildings with architectural green strips (1920s-1930s), 2-5-storey		
Densification in single-family home areas, mixed development with yard and semi-private greening (1870s to present)	Detached, semi-detached and terraced houses (1870s–present)	(semi-)detached and terraced houses
Detached single family houses with gardens		
Villas and town villas with park-like gardens (mostly 1870s-1945)		
Row houses and duplex with yards		
Rental-flat buildings of the 1990s and later	Different multi-family buildings (1990s–present)	Multi-family buildings

2.2. Household survey and ~~analysis with~~ other data sources

In October 2022, people at 10,000 residential addresses in 39 of the 542 PLRs ('Planungsräume' or planning areas) (Landesamt für Bürger- und Ordnungsangelegenheiten, 2022) were invited to participate in our household survey (Table 2). PLRs were selected by stratifying across multiple criteria like heat exposure (Senatsverwaltung für Stadtentwicklung und Umwelt, 2014), population density and representation of different age groups (Amt für Statistik Berlin-Brandenburg, 2022), unemployment levels (Senatsverwaltung für Stadtentwicklung und Wohnen Berlin, 2019) and heat mortality rate (Schuster et al. 2014) to capture a diverse group of people and their behaviour. The 10,000 posted invitations included a QR-code to access the survey online (Evasys GmbH, 2021). To enhance demographic inclusiveness, the letter stated if a respondent had technological constraints, a printed questionnaire could be requested by phone, which were posted in response to received calls. Overall, around 27.2% (N=155) of respondents are classed as "elderly" (65 and older) (Appendix B1). With 565 responses received, only one PLR (No 39, 3 responses) had insufficient responses for analysis.

The survey has questions on household's heat stress perception and experience, living conditions (e.g., building information, green space access), mobility, early warning system, coping measures, adaptation options, and socio-demographic characteristics such as age, income, education and work. Given the focus of this paper, we utilise seven survey topics related to perceived heat and physical and socio-economic factors of people living in different USTs as presented in Table 2.

The household survey perceived heat stress (percentage of people who said slightly hot to very hot in their neighbourhood, Table 2) is compared to the Senate of Berlin's thermal discomfort index (TDI, Table 3). The Senate of Berlin's Urban Climate Planning Information map (Planungshinweiskarte Stadtklima (PHK)) is the TDI source and their basis for considering climate concerns in urban planning

(Senatsverwaltung für Stadtentwicklung und Umwelt, 2015). The PHK assesses thermal situations for meteorological conditions (e.g. daytime (14:00) physiological equivalent temperature, PET, Höppe, 1999, and nocturnal (04:00) air temperature) and local characteristics (e.g., plan area of trees (%) and building volume density in units of m³ ha^{-1}) to assign each block into one of four TDI classes (Table 3) (Senatsverwaltung für Stadtentwicklung und Umwelt, 2015). We translate the TDI class to a value (Table 3) allowing aggregation to PLR scale by an area weighted mean. Other statistical and remote sensing data sources used in our analyses are indicated in Table 3, with all relevant dataset details.

Table 2. Survey questions analysed in this study (original survey number, Q#) with number of respondents (N), that number as a percentage of PLR respondents or USTs (Respond.). Data availability given in Iqbal et al. (2024).

referred to as	Question asked of respondents	Respond. (%)	Q#	N
Perceived heat	*How hot or cool do you think your neighbourhood is during a heatwave compared to the average outdoor temperature for the city?* Much cooler | Slightly cooler | No difference | Slightly hotter | Very hot	% of PLR/ USTs respondents	5.3	558
Housing typologies	*I live in ...* Detached single family house | Semi-detached or terraced single-family house Duplex house | Apartment in a detached multifamily house Apartment in an apartment block (covering part of a floor) | Apartment in an apartment block (covering whole floor) Row block building | Apartment in a multi-family house built in series (block edge development) Others	% of USTs respondents	6.2	561
Open spaces	*How would you describe the area right next to your house/apartment?* Lots of green (trees, meadow, lawn) and plenty of space between the buildings | Lots of green (trees, meadow, lawn), but little space between buildings Little green (trees, meadow, lawn) and a lot of space between the buildings | Little green (trees, meadow, lawn), and little space between the buildings None of this applies to my living environment	% of PLR/ USTs respondents	9.1	543
Age groups	How old are you? 18 to 24 years | 25 to 34 years | 35 to 44 years | 45 to 54 years 55 to 64 years | 65 to 74 years | 75 to 84 years | 85 years and older	% of PLR/ USTs respondents	14.1	564
Health Condition	*Have you already had problems with heat stress? If yes, which ones:* Lethargy/fatigue | Trouble sleeping | Difficulties in concentrating | Dizziness Nausea | Cardiovascular problems | Heat stroke	% of PLR respondents	5.9–5.16	559
Household income	*What is the monthly net income (Netto) of the household? (Netto = after deduction of taxes, social security contributions, etc.)* Less than 900 € | 900 to under 1300 € | 1300 to under 1700 € 1700 to under 2000 € | 2000 to under 2300 € | 2300 to under 2600 € 2600 to under 2900 € | 2900 to under 3200 € | 3200 to under 3600 € 3600 to under 4000 € | 4000 to under 4500 € | 4500 to under 5000 € 5000 to under 6000 € | 6000 to under 7000 € | 7000 € and above Not specified	% of PLR/ USTs respondents	17.8	555
Adaptive measures	*Which of the following measure to protect against heatwaves have you already implemented or are you planning to implement (considering the change of*	% of PLR respondents	12.4	369

	weather in Berlin, as described)? Air conditioner installation Already implemented / In plan/ implementation / Will be an option for future Neither today, nor future / Does not apply			

Table 3. Data compared to survey results. The TDI uses physiological equivalent temperature (PET) values (Höppe, 1999) calculated for the vulnerable population the number of people (#) by age group is considered. Summer months June, July and August (JJA). Data availability given in Iqbal et al., 2024.

Characteristic	Method of determination	Period	Units	Data Source
Thermal discomfort Index (TDI)	Calculated for residents (calm hot 2015 weather) PET (14:00), nocturnal air temperature (04:00), accounting for local tree coverage and building volume, index	Hot summer day	1: Very favourable 2: Favourable 3: Less favourable 4: Unfavourable Weighted mean Block TDI per PLR	Senatsverwaltung für Stadtentwicklung und Umwelt, 2015 GEO-NET, 2015
Urban structure types (UST)	Classification based on building structure, density, open spaces, and representative building use 52 area types grouped into 13 types but are aggregated into 7 USTs classes (Table 1)	2021	1: Dense closed block 2: High-rise buildings 3: Block edge development 4: Multi-family buildings 5: Closed/semi-open block 6: Row development 7: (semi-)detached and terraced houses	Senatsverwaltung für Stadtentwicklung und Wohnen, 2021 and Table A1 provides the basis of new classes
Population Density	Registered residents place of main residence in Berlin	2022	Inhabitants/ hectare	Amt für Statistik Berlin-Brandenburg, 2022
Block age group fraction	[age group population] / [Total Block population]	2022	Population (% per block)	Amt für Statistik Berlin-Brandenburg, 2022
Vulnerable age groups	≥ 65 years; ≤ 5 years (Meade et al., 2020, Dialesandro et al., 2021)	2022	Population (% per ring). Block centroid within a ring included	Amt für Statistik Berlin-Brandenburg, 2022
Plan area fraction of grass	1 m land cover data (2021) aggregated to 10 m to compare summer 2022 state using 10 m normalized difference vegetation index (NDVI from Sentinel-2) (Mitraka et al., 2017)	Cloud free images every 3 days JJA 2022 (54 images)	Fraction per block/ PLR Block fractions use 10 m pixels for centroids within a block boundary but not in a building footprint	Drusch et al., 2012
Plan area fraction of trees	Same data as grass	Same data as grass	Fraction per block/ PLR	Geoportal Berlin (2022a, 2022b) Drusch et al., 2012
Shadow fraction	Hourly shadows from buildings and trees calculated with UMEP (Lindberg et al., 2018) at 1 m pixel resolution	JJA daylight hours	Fraction per block within survey PLR, excluding building footprint	Geoportal Berlin (2022a, 2022b) and Gasco et al., 2014

2.3. Statistical and spatial analysis

In this study, we use overlay analysis and geospatial, descriptive and inferential statistics to answer our research questions. The weighted mean thermal discomfort index of PLRs (Table 3) is compared with perceived heat (Table 2) from the survey using Pearson correlation (section 3.1). To understand what may influence perceived heat stress, we calculate Spearman correlations using human vulnerability data (e.g., age and income) from the survey (section 3.3). Adaptation metrics (e.g., vegetation and shadow fractions) for PLRs are compared with perceived heat using Pearson correlation (section 3.4). Primarily, differences in perceived heat stress are explained by using the respondents USTs (section 3.2). Metric distributions across and within USTs are presented in violin and box plots (section 3.1-3.4). Spearman correlation is used to assess the link between USTs and human vulnerability (age and income) (section 3.3) and Pearson correlation is used to compute the link between USTs, vegetation and shadow indicators (section 3.4). These statistics are calculated using the UST TDIs with numbers assigned as indicated in Table 3.

Analyses use different administrative spatial scales, namely (Fig. 2): Boroughs, PLRs (planning areas) and blocks. The block scale UST (Fig. 2b) data (e.g., grass, trees, and shadow fractions, Table 3) involves aggregating the available raster data (Fig. 2). Analyses include: fraction per block/PLR (grass, trees and shadow) and percentage (%) per block (vulnerable age groups) and ring. A flowchart linking the data sources and analyses is presented in Appendix C1.

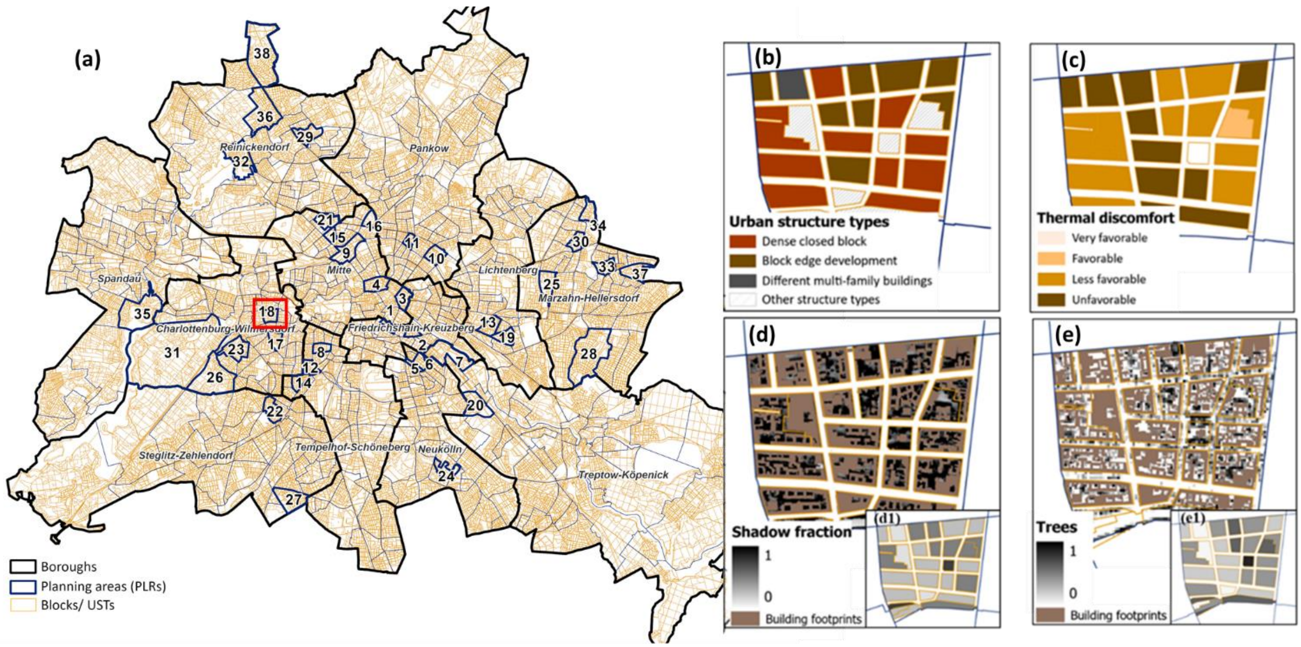


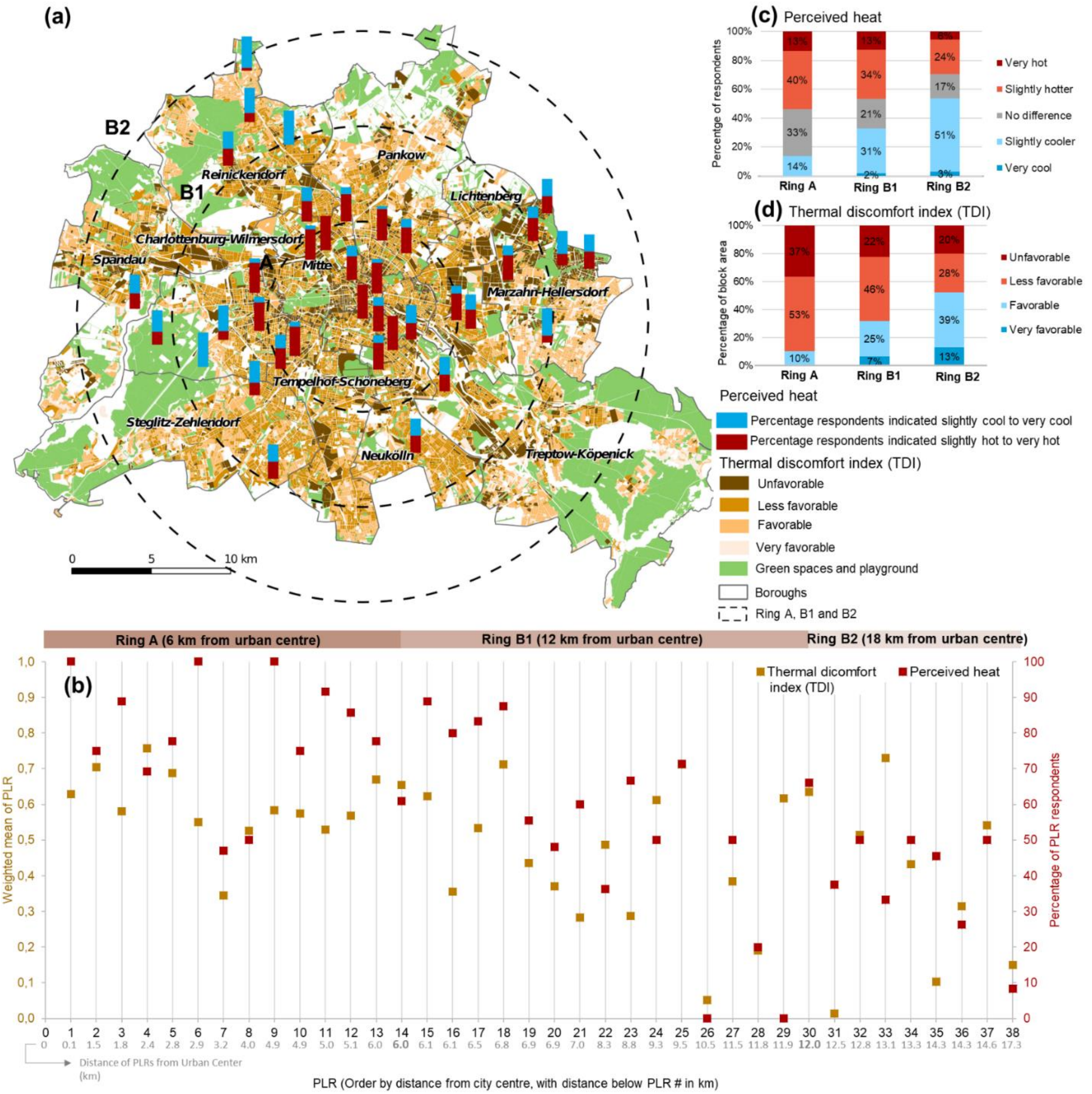
Figure 2. Berlin (a) administrative boundaries showing city (outer line), Boroughs (grey), PLRs (blue, planning areas) and those selected for the household survey (numbered 1 to 38), blocks (orange) and PLR 18 (red box) for which (b) blocks and urban structure types (UST, colour) are shown in PLR (black boundary), (c) thermal discomfort index (colour), and (d) shadow fraction (0=none, 1=maximum) 1 m pixel values and (d1) block mean, and (e) plan area fraction of trees (0 none to 1 maximum) and (e1) block mean.

3. Results

3.1. Perceived heat stress in the 38 PLRs and comparison with thermal conditions

To assess perceived heat stress, survey participants were asked '*How hot or cool do you think your neighbourhood is during a heatwave compared to the average outdoor temperature for the city?'* (Table 2, Q5.3). Across the city, a greater proportion of respondents per PLR living in the city centre (ring A, Fig.1) perceive more heat stress in their neighbourhood than those residing further out (Fig. 3). Overall, the perceived heat (Table 2, Q5.3) and thermal discomfort index (Table 3, TDI) is higher in the ring A PLRs than those in rings B1 and B2. In ring A PLRs (e.g., the boroughs of Mitte and Friedrichshain-Kreuzberg, Fig. 3a) 54% of residents responded that their neighbourhood is hot to very hot compared to 47% and 30% in rings B1 and B2, respectively (Fig. 3b). The differences in perceived heat between rings vary with distance from the city centre (Fig. 3c). However, some PLRs differ from this pattern, like those located in the western borough of Charlottenburg-Wilmersdorf in ring B1 (Fig. 3a, e.g., PLR 17, Fig. 2) and in the eastern borough of Marzahn-Hellersdorf in ring B2 (Fig. 3a, PLR 34, 37, Fig. 2) where 83% and 50% of respondents (Fig. 3b), respectively, perceive their neighbourhood to be hotter than the city average temperature during a heat wave event (Table 2, Q5.3).

Respondents in other PLRs at similar distances from the centre in different parts of the city indicate different perceived heat levels (Fig. 3; e.g., PLR 30 and 35 in ring B2; and 22 and 25 in ring B1). This also occurs in the TDI (Fig. 3). PLR perceived heat (Table 2, Q5.3) and TDI (Table 3) are positively correlated ($r \geq 0.34$, N=38). A poorer correlation is found in ring B1, which may be related to larger areal extents of these PLRs and/or low participant numbers for some urban structure types (USTs). To understand this, UST (e.g., dense block and high rise), socio-demographic profiles (e.g., age, income) and adaptive capacity (e.g., access to or availability of green spaces and shadows) are explored in the following sections.



235 **Figure 3.** Berlin results for 38 PLRs showing (a) responses to perceived heat Q5.3 (Table 2), thermal discomfort index (TDI, Table 3), (b) block weighted mean thermal discomfort index (TDI, Table 3) per PLR (brown, left axis) with 0 indicating all blocks 'very favourable' and 1 all blocks unfavourable and percentage of respondents indicated their perceived heat to be slightly hot to very hot (red, right axis, Table 2, Q5.3) PLR number (#) (Fig. A.1) with distance from city centre and (c) percentage respondents indicated perceived heat from 'very cool' to very hot' by rings (d) percentage of block area of ring from 'very favourable' to

240 'unfavourable' .

3.2. Perceived heat stress and USTs

Respondents report higher perceived heat stress (Table 2, Q5.3) when living in the denser compared to less dense USTs (Fig. 4), with median perceived heat decreasing from: dense closed blocks (hot), high-rise buildings (hot), block edge development (no difference), multi-family buildings (no difference), closed/semi-open blocks (no difference), row development (no difference), and (semi-)detached and terraced houses (cool).

In the dense and closed blocks 67% of the respondents perceive they are living in slightly hotter to very hot conditions relative to average, and 56% of those living in high-rise buildings indicate slightly hotter to very hot condition than average. By contrast, respondents living in closed/semi-open blocks (95%) and row development with green strips (87%) USTs perceive they are in cool to hot conditions. In (semi-)detached and terraced houses, 63% of residents perceive their neighbourhood is slightly cooler to very cool during a heat wave compared to the average outdoor temperature for the city. It is important to note that not only USTs but also their location influence perceived heat stress; e.g., 42% of dense and closed block development is in the ring A (Fig. 1b) where 76% of residents responded that their neighbourhood is slightly hot to very hot (Fig. 3c).

The Spearman statistic test (N=558) indicates significant correlation between USTs (ordered as Table 3) and heat perception (r=0.33 and p=<0.001).

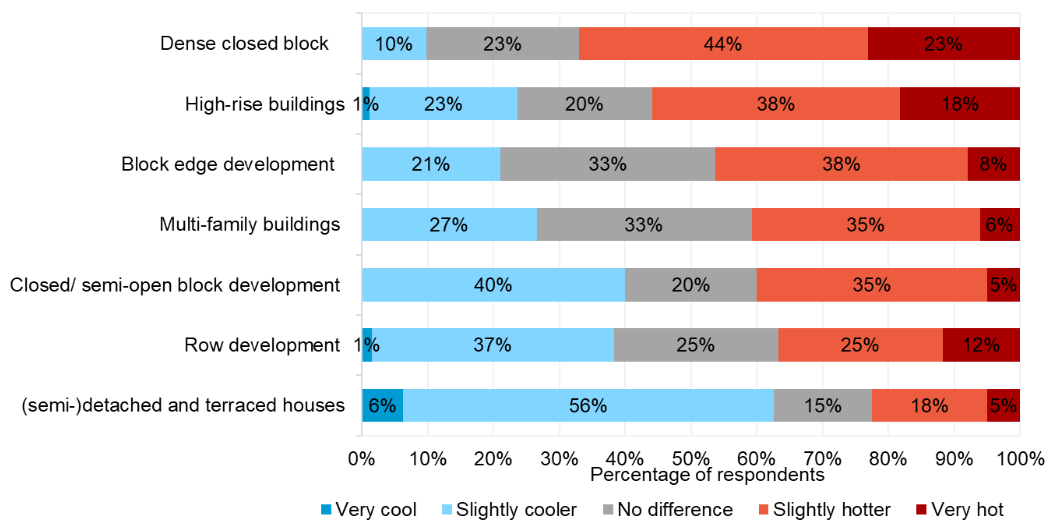


Figure 4. Percentage of UST respondents indicated their perceived heat from very cool to very hot (Table 2, Q5.3)

3.3. Human vulnerability and adaptive capacity

3.3.1. USTs, vulnerable age groups and heat perception

Many studies (e.g., Meade et al., 2020, Dialesandro et al., 2021) identify elderly (≥ 65 years) as an age group vulnerable to heat stress due to underlying health conditions influencing heat related risks. A higher share of >65-year-olds (Table 3) live in (semi-)detached and terraced houses and high-rise buildings UST (Fig. 5a). However, across Berlin the block scale percentage of ≥ 65-year-olds differ, both within and between USTs (Fig. 5b). Overall, more live in (semi-)detached and terraced houses (median: 26%), followed by high-rise buildings (median: 25%) and row development (median: 22%). A relatively lower proportion lives in multi-family buildings and block edge development (median is < 20%). Dense blocks are where elderly residents are least likely to live (median: 10%). A Spearman correlation between the percentage of elderly (≥ 65 years) and USTs (order given in Table 3) in Berlin has a r = -0.541 (p ≤0.001).

Spatial differences are also evident between the rings by age groups (Fig. 5c). Elderly people mostly live in rings B1 and B2, between 6 and 18 km of the centre (Fig. 5c). In ring A, only 13% of the total population are elderly, this increases to 22% (ring B1) and 23% (ring B2, Fig. 6b) in the outer rings. In ring A, elderly people are most frequently living in high-rise buildings, whereas they more frequently live in detached and row houses in rings B1 and B2.

There is a weak correlation (r = 0.086, p≤ 0.004, N=564) between perceived heat and the eight age groups (Table 2, Q#14.1, Appendix B1). This may be linked to 43% of the respondents aged 25 to 64 years report experiencing both high to very high heat due to commuting and spending relatively more time outside. This work-age group tends to live in the urban centre and have high exposure to heat stress. 61% of the ≥ 65 years respondent group report both a high to very high perceived heat and more heat-related health issues (Table 2, Q#5.9–5.16), with more (35.5%) very often experiencing cardiovascular health issues due to heat.

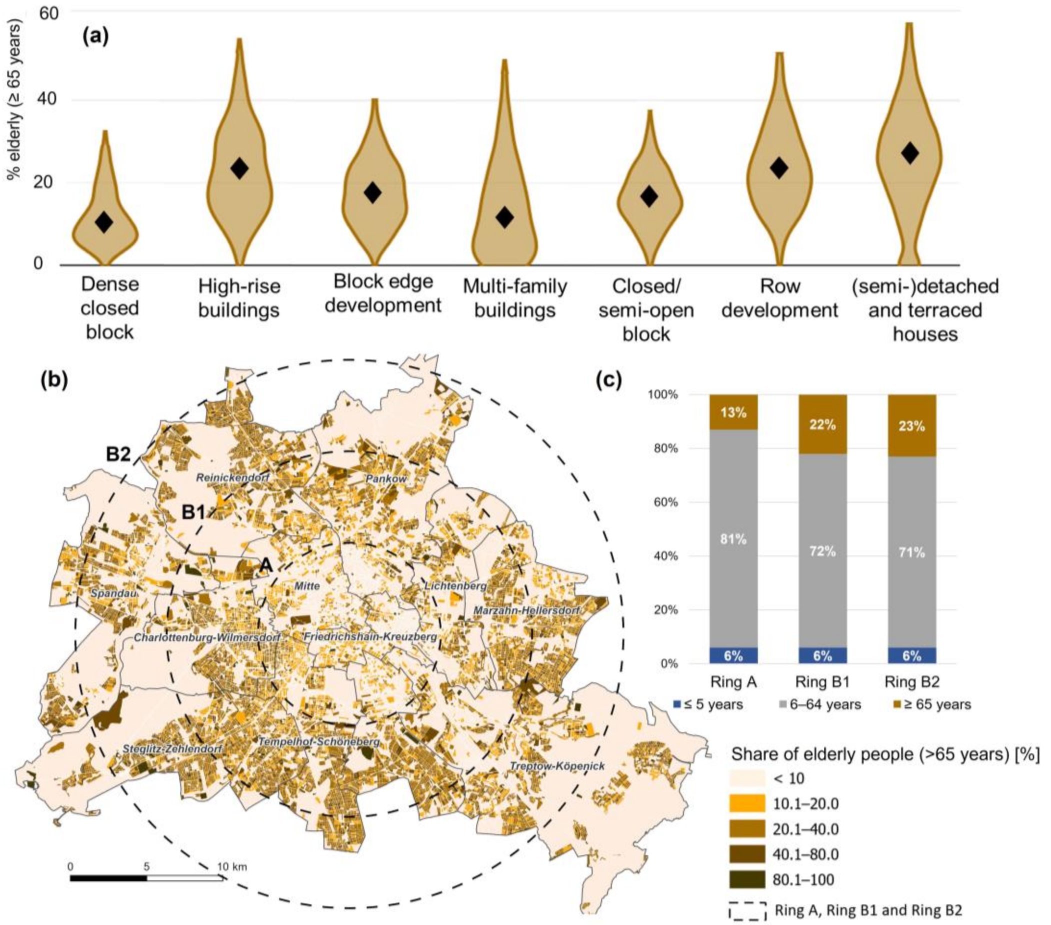


Figure 5. Berlin population who are 65 years or older living in different (a) USTs, (b) block scale (colour, percentage) and (c) by ring for three age groups (colour). Data source and methods: Table 3.

3.3.2. USTs, income and heat perception

Income plays an important role in people's adaptation capacity for challenges exacerbated by climate hazards (e.g., Abrahamson et al., 2009; Hass et al., 2021). Household monthly net income (Table 2, Q#17.8) clustered by UST (Fig. 6) shows most households living in high-rise buildings, block developments and multi-family buildings have incomes close to the overall median (2900–3999€ monthly) of those surveyed. However, 25% of surveyed households in high-rise buildings and 24% in dense closed blocks said their net income is less than 2000€ monthly. Those living in (semi-)detached and terraced houses have the highest median income (4000–4999€). 38.5% of respondents in this UST have monthly net incomes ≥5000€. In the dense closed blocks 27 % report a monthly net income ≥ 5000€ and largest interquartile range (IQR) is for 2000–5999€, indicating households from many different income groups live in this UST (Fig. 6).

Spearman correlation between USTs (order, Table 3) and household income is weak (r = 0.22) but significant (p = <0.001). There is a weak but statistically significant (p ≤0.001) negative correlation (r = -0.15) between household income and perceived heat; i.e. higher incomes are correlated with lower perceived heat stress. This appears conceptually logical as higher adaptive capacities are expected in wealthier households (Laranjeira et al., 2021). With 37% of surveyed households with net monthly income ≥5000€ indicating they had an air conditioning system, the results indicate a relationship between adaptive capacities and available financial resources.

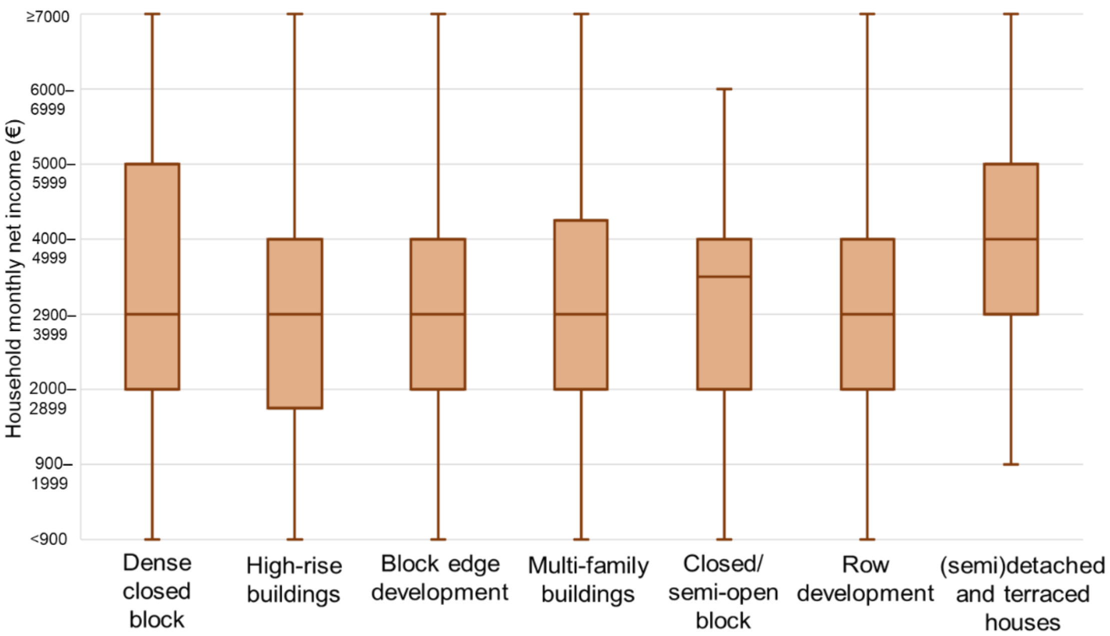


Figure 6. Monthly net household income (Table 2, Q#17.8) by UST showing median (line), IQR (box) and minimum and maximum values (whiskers). Note that the y-axis uses nonlinear classes.

3.3.3. USTs, availability of vegetation and heat perception

Urban vegetation can support heat stress adaptation by offsetting or buffering adverse heat impacts (Marando et al., 2022; Schwaab et al., 2021). The plan area fraction of grass and trees is estimated using summer 2022 Sentinel-2 10 m pixel NDVI values excluding building footprint, with local both 1 m resolution land cover and tree height (Geoportal Berlin 2022a, 2022b) used to compute values for all USTs across Berlin (Table 3, Fig. 2).

The grass to tree fraction differs between USTs (Fig. 7) from similar (e.g., high-rise buildings, row developments), to higher fraction of trees than grass, and the reverse of higher grass fractions (cf. trees) (e.g. (semi-)detached and terraced). The overall median fractions (diamonds, Fig. 7) also vary, with (semi-)detached and terraced houses having comparatively high fractions of both grass (0.37) and trees (0.23), followed by row development (grass: 0.27, trees: 0.28) and large estate buildings (grass: 0.23, trees: 0.25), and multi-family buildings (grass: 0.20, trees median 0.10). Dense closed blocks have very low fraction of grass (0.04) and trees (0.13) relative to other USTs. The correlation between fraction of vegetation and USTs (order, Table 3) is significant (p=0.01) with a correlation coefficient of 0.778 which denotes higher association between USTs and vegetation fraction.

Vegetation fraction is a property assessed when delineating the analysis rings (Fenner et al. 2024), with ring A having less vegetation, where predominantly block structures exist. The outer rings have more vegetation and less building volume (Fenner et al. 2024, their Fig. 2) where the share of (semi-)detached and terraced houses are higher (Fig. 1b). A statistically significant correlation ($p<0.001$) between availability of green (Q#9.1) and perceived stress (Q#5.3) survey results is found with a correlation coefficient of 0.29.

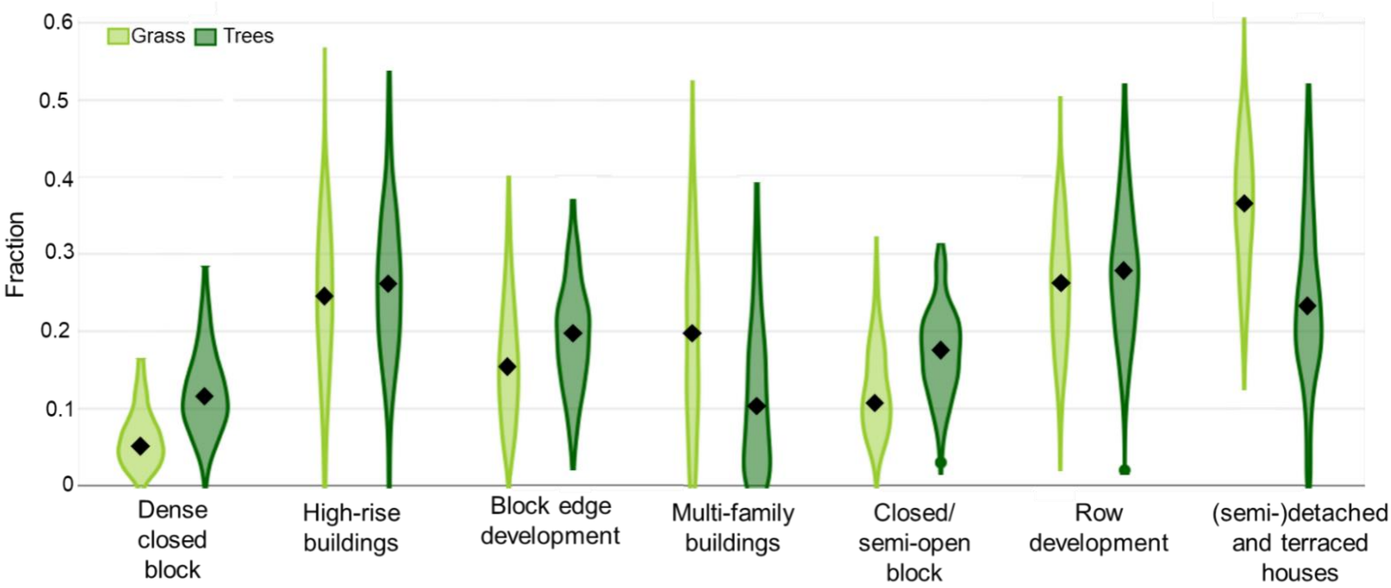


Figure 7. Inter-block variation and median (diamond) in grass and trees fraction (colour) by urban structure type (UST) with (Data source and method: Table 3, Fig. 2).

3.3.4. USTs, availability of shaded spaces and heat perception

Shading from trees and buildings is well known to create cooler areas (e.g., Lindberg and Grimmond, 2011; Bäcklin et al., 2021; Turner et al., 2023). Shadow fractions from buildings and trees are calculated during daylight hours for all summer days (June, July, August) for each block in the surveyed PLRs (Table 3, Fig. 2).

The lowest median shadow fraction across the different USTs (Fig. 8) is for dense closed blocks (0.36), consistent with low fraction of trees (Fig. 7). The large estate high-rise buildings have one of the highest median shadow fractions (0.61) linked to the tall buildings and the presence of trees in this UST (Fig. 7). Shadow fractions are highest in row development with landscape green strips (median: 0.63) and (semi-)detached and terraced houses (median: 0.61).

Large variations of shadow fraction occur between and within USTs. The greatest variability occurs within the multi-family building UST (IQR= 0.26) followed by (semi-)detached and terraced houses (IQR=0.15). Median shadow fraction by rings for the surveyed PLRs increases from 0.43 in ring A to 0.61 ring B2, which is linked to increase in trees cover. Pearson correlation between USTs (order, Table 3) and shadow fraction is strong and significant ($r=0.55$, $p=<0.001$), i.e., increasing with more shaded fraction per USTs. From the survey data, a significant ($p<0.04$) correlation coefficient of -0.33 is found between shadow fraction and perceived heat, indicating reduced perceived heat stress with greater shadow fraction. Again, this is conceptually consistent with the expectations.

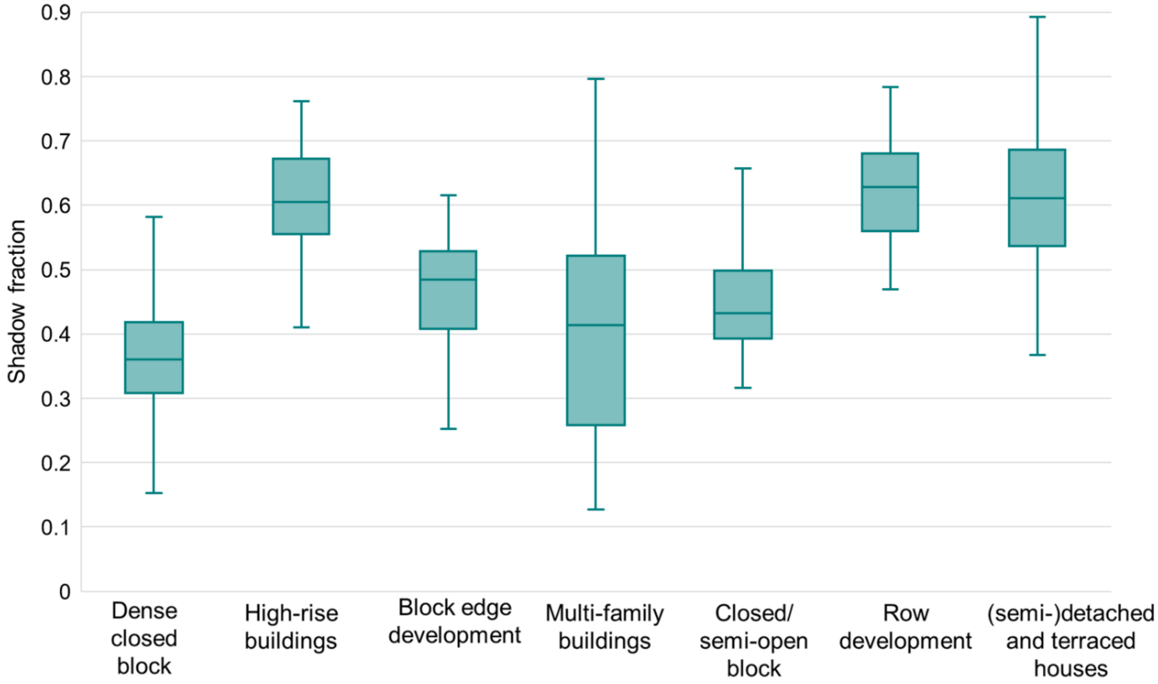


Figure 8. Summer (June, July, August) shadow fraction by UST with variability between blocks showing median (line), IQR (box) and minimum and maximum values (whiskers) (Data source and method: Table 3, Fig. 2).

4. Discussion

Our assessment of perceived heat stress with urban structure types (USTs), people's age and income and neighbourhood location relative to the city core of Berlin demonstrate heat stress and adaptive capacities are perceived differently in various USTs and city rings.

Simplifying the city to three rings, we find a significant correlation between measured thermal discomfort and inhabitants' perceived heat stress with distance from the centre of the periphery of Berlin (i.e., reducing from ring A→B1→B2). These results are consistent with those reported for Munich, Germany, across the city gradient (Heldens et al., 2013). In ring A, 76% of respondents report slightly high to very high heat stress, and in ring B2 nearly a third of the respondents still report high to very high heat stress. Our analysis finds the UST people reside in is correlated with their perceived heat levels. In ring B2, high perceived heat stress occurs in high-rise buildings particularly in the borough of Marzahn-Hellersdorf and in multi-family buildings in Reinickendorf. Although high-rise buildings occur in all three rings, the inner ring (A) is generally more densely built-up with a larger building volume (Fenner et al. 2024). In ring A, higher percentage of dense closed block structures lack the availability of vegetation and shadow accounts for climate adaptation. Thus, urban renewal projects and urban development concepts need to address both the climatic conditions within the inner city and the protection and development of green space and shaded areas within districts where certain USTs, e.g., high-rise and multi-family buildings, occur.

Across USTs, differences in perceived heat stress exist, as do different age groups. Notably, the elderly population have a high tendency to live in (semi-)detached and terraced houses (26%), high-rise buildings (22%) and row development (18%), particularly in ring B1 and B2. Given age-related susceptibility and heat-related health problems (section 3.3.1), this vulnerable population needs addressing in the outer-city (e.g., ring B1 and B2). Although these households often live in single family homes, high-rise and multi-family buildings, with access to (shaded) green space, additional urban adaptation strategies such as inclusive public and open spaces and community centres could improve the demographic mix within these areas. With fewer elderly (16%) in ring A, more younger population groups are exposed to heat stress in the inner city. However, their – on average – better physical condition and overall health should be better able to buffer some of the adverse health impacts. Consequently, different urban adaptation strategies are needed for the various USTs, but location (inner/outer city ring) as well as social composition also should be considered. Differential adaptive capacities between different USTs should inform the next generation of urban adaptation plans.

Overall, the integrated analysis and assessment undertaken shows that not only the exposure to heat stress matters for urban adaptation, but also socio-demographic composition, including the consideration of differential adaptive capacities in terms of access to shaded green space and economic circumstances (e.g., income) need to be adequately considered. Particularly, areas with high concentrations of elderly and/or challenging socio-economic conditions (e.g., lower income groups) require planned adaptation and support for adaptation. While elderly wealthier households in single family homes may be able to afford private adaptation measures to reduce heat stress, such as air-conditioning, the elderly living in high-rise and multi-family buildings in the periphery (e.g., Marzahn-Hellersdorf and Reinickendorf) need more attention. Environmental injustice due to lack of access to green cooling areas for vulnerable populations is found in 14 major European urban areas by Rocha et al. (2024). Thus firstly, urban development policies should address the aging population process. Secondly, socio-economically disadvantaged groups and elderly living in more dense urban structures, such as high-rise buildings, typically do not have access to private green space particularly in inner urban areas. Therefore, public planning policies need to ensure that with increasing densification, green space quality and access need to be secured for those living without a garden. This may be easier in large estate and high-rise buildings in the outer city region, but in both ring A and B1 such USTs exist which requires attention in the adaptation.

Finally, understanding spatial patterns of thermal discomfort and heat stress is critical for targeted interventions to improve the liveability of urban areas in the context of climate change. The characterization of urban form using USTs and city rings allows for a detailed understanding of the variability in perceived heat, human vulnerability, and adaptive capacity across different spatial scales. This nuanced approach supports more targeted interventions for urban development and climate change adaptation. Beyond studying urban gradient across city rings, our approach allows a detailed study on spatial variability at neighbourhood (block) scale within the rings by an introduction of USTs. This integrated assessment approach of urban form with social fabric provides additional information on more specific adaptation requirements. It should be noted that we analysed the human vulnerability in the USTs only connected to residential uses. Working population especially those working outside and their vulnerability is not addressed in this study due to lack of data (e.g., about working conditions and perception of people about heat stress at work). Furthermore, differentiation between private and public green spaces across UST and city rings is not captured which can influence heat stress perception (Sousa-Silva and Zanocco, 2024). Nevertheless, we suggest the linkages between USTs, vulnerable population and their differential adaptation capacities across city rings should be tested in other cities as well which can facilitate inter-city comparative studies. City size, physical and social composition, typography and climate cannot be ignored in terms of the transferability of results of this study to other cities.

5. Conclusions

In this study, we take a multi-dimensional approach combining perceived heat with urban morphology and socio-economic structure that provides essential information for enhancing adaptation towards heat-stress. This approach is based on (1) incorporating the social dimension, currently not sufficiently addressed in climate adaptation, (2) identifying the characteristics of USTs which support social structures, and (3) employing quantitative methods to study social and physical structures across the city gradient. Together they can inform recommendations for future climate adaptation plans, considering the physical and social fabric of the city. This approach is exemplified in the city of Berlin. The findings show that perceived heat exposure decreases with the distance to the urban centre, while human vulnerability and adaptive capacities depend stronger on inner variations in and differences between USTs. Therefore, USTs matter and can be linked with demographic and socio-economic information for assessing aspects of exposure, human vulnerability and adaptive capacity.

Although UST focus on the physical structure, a deeper understanding is obtained by coupling this with socio-economic structures, human vulnerability and adaptive capacities where statistically significant correlations are found. The analysis indicates a heterogeneity in perceived heat stress and vulnerability profiles within and amongst USTs. Collectively, this approach will facilitate the identification of specific local adaptation needs to be addressed in future risk management strategies in civil protection and strategic urban planning. However, urban planning responses to climate change also require a better understanding of dynamic exposure patterns (e.g., day and night) and vulnerability. Moreover, heat-related aspects at various places (e.g., in houses/apartments, in the city centre, during work and school), and while commuting need to be captured more precisely (e.g., Hertwig et al. 2025). Combining people's behaviours through dedicated surveys need to be investigated and integrated into climate adaptation plans. There is a need for dedicated studies to investigate demographic shifts and urbanization processes for identifying urban transformation pathways (Kaveckis, 2017). In this respect, physical (e.g., tree growth) and social transitions (e.g., aging population, work force changes) over time need to be accounted for in adaptation plans.

Data availability statement.

All presented data are available at https://doi.org/10.5281/zenodo.12192376.

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Author contributions

NI, MR, GS, JB, SG and DH conceptualised the study. NI, MR, and ZM curated the data. NI, MR, JB and SG developed analysis methodology. NI performed the analysis, with visualisations and drafted the manuscript. NI, MR, JB, SG, DH, ZM and NC wrote and revised the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

6. Appendix: Additional Information

Table A1. Criteria used to aggregate Berlin's UST, with the 5 - 95 percentile range given.

Characteristics	Source	Large estate with high-rise buildings	Dense block develop. closed rear courtyard	Closed block develop. rear courtyard	De-cored block-edge develop. post-war gap closure	Block-edge develop. with large quadrangles	Closed & semi-open block develop. decorative & garden courtyard	Parallel row buildings with architectural green strips	Free row development with landscaped residential greenery	Row houses and duplex with yards	Densification in single-family home areas.	Detached single family houses with gardens	Villas with park-like gardens	Rental-flat buildings
# Storeys	Geoportal Berlin, 2023	4.1–10.9	4.5–5.6	3.7–5.6	3.3–6.1	2.6–5.0	2.7–4.8	2.0–4.3	2.3–5.6	1.0–2.9	1.4–3.3	1.1–2.2	1.4–3.0	1.0–6.6
# Respondents	Household survey 2022	97	27	56	65	98	20	17	52	45	4	24	7	50
Building age	Geopotal Berlin, 2016	1960s–1990s	1870s–1918	1870s–1918	after 1945	1920–1940	1870s–1918	1920s–1930s	1950s–1970s	Un-specified	1870s–present	Un-specified	1870s–1945	1990s–present
Inhabitants/ha	Amt für Statistik Berlin-Brandenburg, 2022	136–479	263–681	184–594	152–505	118–423	99–404	68–320	68–296	20–132	33–143	20–68	14–115	56–434
Green volume number [m³/m²]	Geoportal Berlin, 2020	0.6–5.9	0.8–3.0	0.9–3.9	1.0–5.1	1.2–5.4	1.3–4.7	1.6–8.8	1.8–7.2	0.2–6.1	1.4–8.2	0.7–6.7	1.7–8.3	0.1–5.5
Degree of sealing [%]	Geoportal Berlin, 2021	31.2–63.0	78.3–91.4	64.9–89.6	51.3–84.6	40.6–72.9	46.4–82.2	29.7–62.0	27.0–58.6	21.0– 50.1	25.3–50.1	21.4–40.5	20.1–49.5	33.8–84.6
Floor space index	Geoportal Berlin, 2019	0.72–2.34	2.44–3.76	1.51–3.44	0.98–2.90	0.64–2.24	0.68–2.45	0.30–1.56	0.37–1.47	0.09– 0.68	0.22–0.82	0.12–0.40	0.16–0.72	0.00–2.64
Floor area ratio	Geoportal Berlin, 2019	0.12–0.36	0.53–0.72	0.39–0.68	0.29–0.65	0.23–0.51	0.25–0.58	0.13–0.39	0.14–0.35	0.10– 0.30	0.15–0.30	0.11–0.23	0.11–0.29	0.00–0.64
Satellite view	Senatsverwaltung Stadtentwicklung und Wohnen, 202													
Building block plan	Senatsverwaltung Stadtentwicklung und Wohnen, 2020													
3D view	Senatsverwaltung Stadtentwicklung und Wohnen, 2020													

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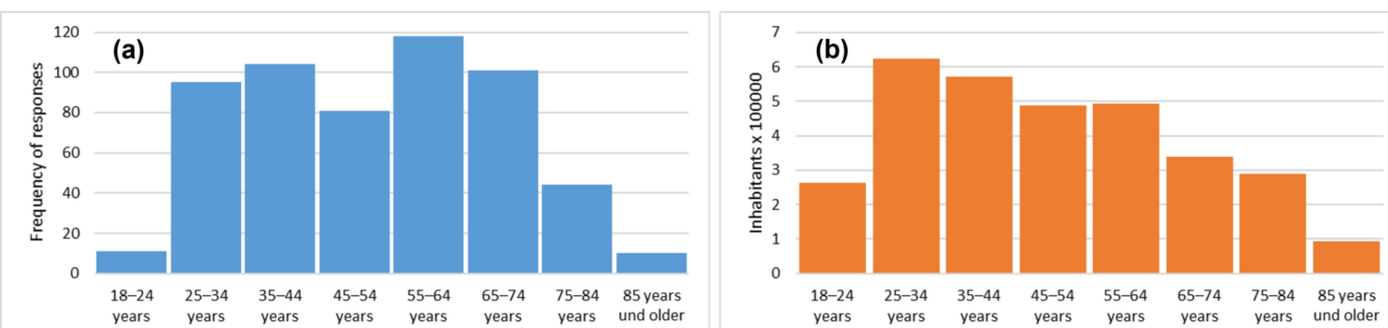
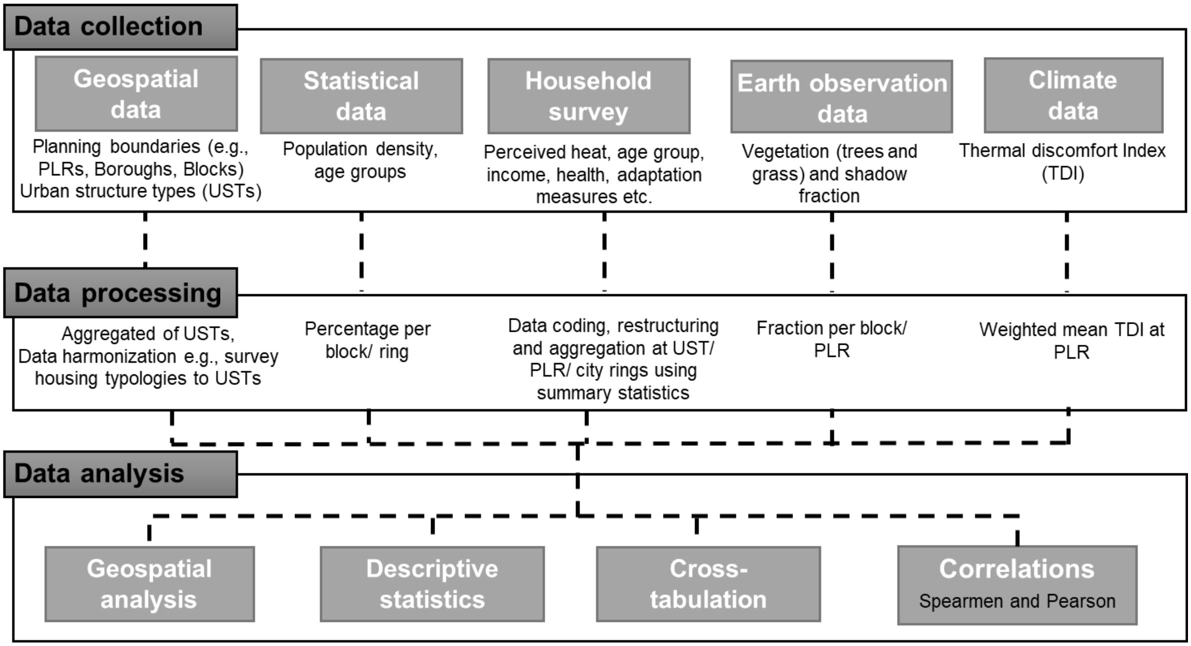


Appendix B1. Age-group histograms of (a) survey respondents and (b) the population of Berlin from Statistisches Bundesamt, 2022.



Appendix C1. Flow chart linking the data sources and analyses.

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