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Assessment of heat-related adaptation options across different households and urban structure types in transforming cities: Case study Berlin☆

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A R T I C L E I N F O

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A B S T R A C T

Heat-related risks pose a significant challenge to public health; therefore, the topic has gained increased attention in science and policy. As climate change accelerates, integrating adaptation strategies into urban planning is essential for risk management. However, urban adaptation plans often underrepresent household adaptive capacities and their priorities regarding adaptation actions. To adequately explore these aspects, the present study assesses the willingness of adaptation decisions undertaken by different socio-economic groups across residential urban structure types (USTs) in Berlin, Germany. A large household survey encompassing 569 households form the basis of this assessment. Descriptive statistics, bivariate correlation, and Poisson regression revealed how USTs, socio-economic factors and heat-specific adaptive capacity influence households' behaviour (e.g., activity patterns and ventilation) and implemented structural adaptation measures (e.g., shading and building insulation). While household previous experience, preparedness and expectations towards authorities influence behavioural adaptation, structural measures are more dependent on USTs, ownership status, household size etc. The empirical data show that households living in (semi-)detached and terraced houses, owners and those living with a family are more likely to implement structural adaptation measures. Existing and future urban adaptation plans focusing on heat-sensitive urban planning can employ this method to plan and monitor adaptation actions across different urban structures.

1. Introduction

Anticipated climate change is projected to disrupt the historically established relationship between urban environments and their climatic conditions in an unprecedented manner. The conceptual baseline of "normal" climate will undergo a substantial redefinition (Lewis et al., 2017). The 2003 European heatwave, which resulted in more than 70,000 excess deaths (Robine et al., 2008), was considered an extraordinary event at the time (Stott et al., 2004). By mid-century, however, summers of comparable severity are expected to occur very often, and by the end of the century, the summer of 2003 may be regarded as anomalously cool (Mora et al.,

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2013; Lewis et al., 2017). Considering rising temperature and heat waves in recent years (Marcotullio et al., 2022) (e.g., extreme heatwaves in South Asia, 2024, European heatwaves 2022, North American Pacific Northwest heatwave 2021, South Africa heatwave of 2016), it is clear that warming is no longer a projected phenomenon, but it is a living reality.

In this context, mitigation efforts alone do not suffice to address the impacts of climate change; therefore, societies must adapt to the frequent and extreme weather events and climate hazards. The IPCC's sixth assessment report states that an increasing recognition of climate-related risks has led at least 170 countries and numerous cities, to integrate adaptation actions into their planning processes and climate-related policies (high confidence) (Adelekan et al., 2022). The process comprises of local risk assessments based on scientific information and diverse knowledge systems including indigenous knowledge and practitioner expertise. This assessment formulates a basis of specific urban adaptation options to manage risk in natural, human and ecological systems including nature-based solutions, reinforcing institutional capacities, social innovation, and planning policies such as early warning system, planned relocation and enhanced health services (Lee et al., 2023). Nowadays, private sector uptake in adaptation actions is made certain by law, regulations, and subsidies along with government-led initiatives (Uittenbroek et al., 2019; van der Heijden et al., 2019; Filatova et al., 2025). Despite efforts, observed adaptation actions are often fragmented, limited in scale, and lack cross-sectoral approach (IPCC, 2022). Therefore, the gap between current and required adaptation level is widening particularly amongst more vulnerable groups (Turek-Hankins et al., 2021). For instance, Rocha et al. (2024) revealed that underprivileged groups such as unemployed, tenants and immigrants have below-average access to green cooling in European major urban areas including Paris, Madrid, Berlin, and Milan. Similarly, canopy maps capture stark inequalities in Phoenix (USA) and Melbourne (Australia) where low-income and minority neighbourhoods remain heat-exposed with low greening and shading (Nelson et al., 2021; Sharifi et al., 2021).

It is often argued that possession of adaptive capacity is a fundamental prerequisite for the effective implementation of adaptation actions (Engle, 2011). However, it remains uncertain whether implementation of adaptation options can truly be inferred from mere capacity to act (Mortreux et al., 2020). The literature underscores many cases where adaptive capacity does not inevitably reflect into actual adaptation actions (Mortreux et al., 2020; Schubert et al., 2025). When adaptation does occur, it appears to be driven less by the availability of resources and more by the hazard-related specific adaptive capacity such as previous experiences with extreme events, place attachment, and trust in authorities (Elrick-Barr et al., 2014; Mortreux et al., 2020; Chapagain et al., 2025). Conversely, evidence shows that adaptation can also emerge within social systems that appear to have low adaptive capacity such as the proactive riverbank conservation by low-income communities in Indonesia (Wicaksono et al., 2022) and solar-reflective roof coating, e.g., white-lime paint, to increase building facet albedo in the slums of Ahmedabad, India (Vellingiri et al., 2020).

Urban areas are heterogeneous with varying physical and social characteristics (Liu et al., 2025). However, urban/spatial planning strategies focusing on climate risks often curtail only physical urban typologies and underrepresent the social dimensions (Birkmann et al., 2019; Turek-Hankins et al., 2021; Wendnagel-Beck et al., 2021; Eldesoky et al., 2022; Iqbal et al., 2025). Nevertheless, integrating climate change adaptation into new urban planning, plans and development activities requires a cross-sectoral approach which has to be sensitive towards needs and requirements of different societal groups in the context of climate justice as indicated by Bullard (2000). Integrating the human dimension into adaptation plans requires moving beyond spatial analyses of aggregate demographic data to a deeper understanding of people's knowledge, attitudes, practices, and preferences regarding extreme heat. In this process, local knowledge systems play an essential role in shaping adaptation strategies (IPCC, 2022), yet remain underexplored in climate change research. The literature identifies a discrepancy between the actions policy experts recommended and the measures local communities actually adopt (Haque et al., 2017; Bremer et al., 2019). Therefore, collecting survey data at household level is crucial to comprehensively assess a population's status and capacity to adapt to extreme heat in varied socio-physical systems. Understanding the barriers such as ownership status or financial limitations to implement certain options is critical, and such information must be gathered at the household level. By focusing on Berlin and its diverse urban structure types and households, the study recognizes that effective climate adaptation requires granular insights where specific neighbourhoods and households are the focus. Considering these research gaps, the present study answers the following research questions:

- How can a survey-based analysis underscore the household adaptive capacity and willingness to implement heat-related adaptation options in Berlin?
- Do heat-related adaptation options at household scale differ by urban forms?
- Do heat-related adaptation options at household scale differ amongst socio-economic groups?
- Which factors influence the decision of households regarding implementation of structural and behavioural adaptation measures?
- How can the knowledge about adaptation status amongst urban form and socio-economic groups inform heat adaptation plans and urban planning?

We answer these questions by examining and conceptualizing household adaptive capacity and heat-related adaptation options in the context of the city of Berlin in Section 2. Section 3 describes the methodology employed in this study, including description of the study area, survey design and data analysis. It also highlights the selected regression model and its evaluation. Section 4 presents the results of statistical analysis including descriptive statistics, bivariate correlation and Poisson regression modelling. Finally, Section 5 discusses main conclusions, points out limitations and emphasizes the implications of the study's findings.

2. Conceptualizing adaptive capacity and adaptation options at household scale

2.1. Definitions

The IPCC (2022) defined adaptive capacity as 'the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences' (MA, 2005). Adaptive capacity is context-specific, multi-faceted and differs across various spatial levels such as global, national, states, communities, households and individuals (IPCC, 2022). However, across all scales, adaptive capacity emerged as a positive component that decreases the vulnerability associated with climate risk (Engle, 2011; Chapagain et al., 2025). Scholars argued that there are various dimensions such as physical assets, social capital, human assets and communication etc. that can frame the individuals' abilities to deal with hazards (Engle, 2011; Elrick-Barr et al., 2014; Nhuan et al., 2016; Chapagain et al., 2025). One framing categorizes the adaptive capacity into two groups i.e., generic adaptive capacity and specific adaptive capacity (Guardaro et al., 2022). While specific adaptive capacity captures the individual's ability to respond to a specific climate hazard e.g., heat stress, generic adaptive capacity is wider and it explains the individual's ability to handle social, financial and political stressors (Guardaro et al., 2022). Past experiences with climate hazards, risk perception, awareness and preparedness shape the specific adaptive capacity of households (Guardaro et al., 2022). Income, physical assets and education constitutes generic household adaptive capacity (Lemos et al., 2016).

Adaptation options are 'the array of strategies and measures that are available and appropriate for addressing adaptation. A broader range of actions and measures can be categorized into structural, behavioural, institutional, and ecological components' (IPCC Glossary, 2022). Amongst these, the present study concentrates on two dimensions (Fig. 1) proposed by UNDRR (2015): structural and behavioural adaptation. At household level, behavioural adaptation refers to the coping mechanism of individuals to adjust to the rising temperatures (Navas-Martín et al., 2024). As the term implies that the adjustments occur at the personal level without altering the surrounding environment. For example, intuitive decision-making by adjusting activity patterns, reducing outdoor heat exposure, and ventilating the dwelling at cooler hours (Coley et al., 2012). In contrast, structural adaptation measures include changing the living environment either actively or passively to create cooler conditions (Navas-Martín et al., 2024). Such actions may include operating shading devices, using fans or ventilators, installing air-conditioning systems, window glazing or planting (Coley et al., 2012). Fig. 1 presents the conceptual framework used in the study constituting generic and heat-related specific adaptive capacity and adaptation actions implemented in the context of heat stress as a climate hazard.

2.2. Identifying indicators for household scale adaptive capacity and heat related adaptation options

Based on previous capacity action studies (Nhuan et al., 2016; Mortreux et al., 2020; Guardaro et al., 2022; Navas-Martín et al., 2024; Chapagain et al., 2025), we compiled a comprehensive list of indicators (Table 1), regardless of conflicting hypotheses, findings or results. To ensure comparability, indicator selection focuses exclusively on quantitative empirical studies examining the capacity–action relationship. All indicators are widely used to in the scientific literature.

Grouping indicators that are semantically equal (e.g., social connectivity and social capital) and prioritizing those that are relevant for the German context, resulted in 10 and 6 indicators for generic and heat-related adaptive capacity, respectively. Adaptation actions are grouped into 10 structural measures regarding climate-optimization of buildings, shading and solar control, ventilation, cooling and green infrastructure within building premises. 12 non-structural or behavioural adaptation measures include adjusting activity patterns, ventilation, personal adjustments and relocation intention of households. These indicators are operationalized in the context of the Berlin household survey as a data gathering method, therefore, most of the conventional statistics at local scale do not sufficiently capture structural and behavioural measures linked to adaptive capacities.

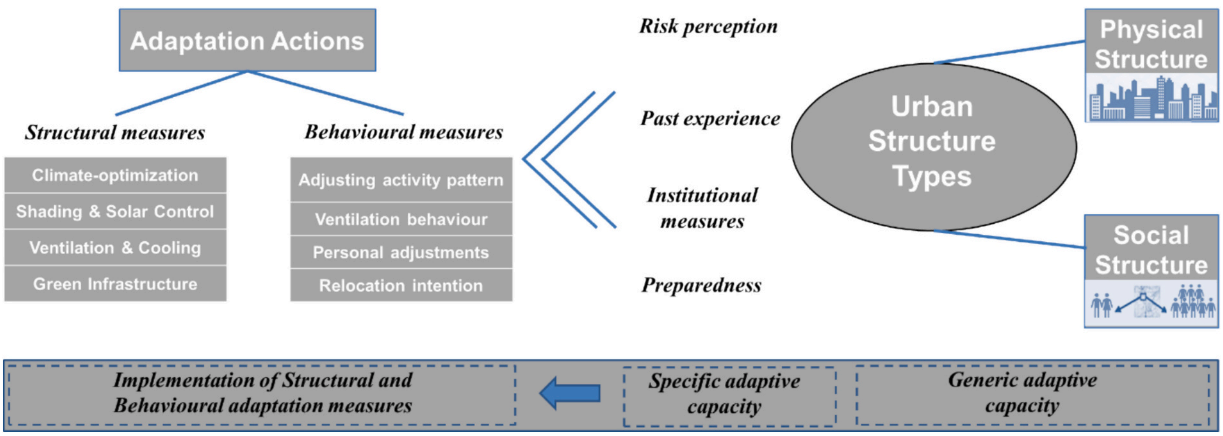

Fig. 1. Conceptual framework presenting generic and heat-related specific adaptive capacity and adaptation actions.

Table 1
Conceptualisation of indicators for socio-physical urban structure, heat-specific household adaptive capacity and heat-related adaptation measures (structural and behavioural).

Category	Sub-category	Indicators	Definition used in this study	Evidence from the literature
Specific adaptive capacity	Heat-related adaptive capacity	Risk perception	Perceived heat stress risk in the residence	Nhuan et al. (2016); Mortreux et al. (2020); Guardaro et al. (2022)
		Past experience	Experience with the impacts of heat stress on daily routine	Nhuan et al. (2016); Mortreux et al. (2020); Guardaro et al. (2022)
		Institutional measures	Knowledge about early-warning systems	Chapagain et al. (2025)
			Expectations towards authorities	Chapagain et al. (2025)
			Knowledge on self−/household protection measures against heat stress	Chapagain et al. (2025); Nhuan et al. (2016)
		Preparedness	Perceived ability to protect the residence against heat stress	Nhuan et al. (2016); Mortreux et al. (2020); Guardaro et al. (2022)
Generic adaptive capacity	*Physical structure*	Urban structure type	Classification of building typology subject to building structure, density and open spaces etc.	Nhuan et al. (2016); Taylor et al. (2018); Ahmed et al. (2025a); Muñoz et al. (2025)
			Building age	Beckmann et al. (2021a)
	Social structure	Age group	Age group of household head/respondent age	Beckmann et al. (2021b); Sandholz et al. (2021)
		Household size	Number of household members	Ahmed et al. (2025a)
		Financial resources	Ownership status of the residence	Hayden et al. (2017); Hong et al. (2023); Ahmed et al. (2025a)
			Approximate net monthly household income	Mortreux et al. (2020); Sandholz et al. (2021)
			Willingness to pay for structural measures	Elrick-Barr et al. (2014)
		Education	Highest educational qualification of household	Nhuan et al. (2016); Hayden et al. (2017); Mortreux et al. (2020)
		Residence duration	Number of years living in same dwelling	Nhuan et al. (2016); Mortreux et al. (2020)
		Social network	Support from neighbours (e.g., in case of medical emergency)	Nhuan et al. (2016); Schubert et al. (2025)
Adaptation actions	*Structural measures*	Climate-optimization of building	External walls and roof insulation	Coley et al. (2012)
			Light-colour coating of external walls/roof	Coley et al. (2012)
		Shading and solar control	Shading devices (awnings, blinds)	Navas-Martín et al. (2024)
			Heat-proof windows/frames	Coley et al. (2012)
		Ventilation and cooling	Potential to cross-ventilate	Beckmann et al. (2021b)
			Cooling device (e.g., fans)	Beckmann et al. (2021a); Beckmann et al. (2021b)
			Air conditioning	Beckmann et al. (2021b)
		Green infrastructure	Planting/trees/water areas in garden/balconies	Beckmann et al. (2021b)
			Green roofs	Tseliou et al. (2023); Harbiankova and Manso (2025)
			Facade greening	Tseliou et al. (2023); Harbiankova and Manso (2025)
	Behavioural measures	Adjusting activity pattern	Adjusting working hours on hot days	Teebken et al. (2023)
			Moving outdoor activities to mornings and evenings	Navas-Martín et al. (2024)
			Avoiding particularly hot places (e.g., city centre, main streets)	Navas-Martín et al. (2024)
			Visiting cooler places outside (e.g., park, forest, outdoor pool)	Navas-Martín et al. (2024)
		Ventilation	Changing sleeping place	Beckmann et al. (2021b)
			Ventilating residence at night, morning and/or evening	Coley et al. (2012); Beckmann et al. (2021a); Navas-Martín et al. (2024)
			Keeping windows and/or shutters/blinds closed during the day	Beckmann et al. (2021b)
		Personal adjustments	Increasing water intake	Ahmed et al. (2025b)
			Adjusting clothing to heat (e.g., sun hat, long loose clothing)	Teebken et al. (2023); Navas-Martín et al. (2024)
		Relocation intention	Selecting/relocating to a heat-adapted residence (e.g., with good ventilation and lots of green spaces)	Beckmann et al. (2021b); Laranjeira et al. (2021)
			Selecting/relocating to a heat-adapted living environment/neighbourhood (e.g., with sufficient supply of cold air and green areas)	Laranjeira et al. (2021)
			Choosing a heat-adaptive workstation (e.g., with adequate shading and good ventilation)	Laranjeira et al. (2021)

3. Methods

3.1. Berlin context

Berlin is situated in the temperate climatic zone and confronted with the consequences of climate change on a daily basis whether in media reporting, political debates or health consequences. The statistical office has reported that the average excess mortality due to heat is 205 deaths per year in the period from 2018 to 2024 (Fig.2., Amt für Statistik Berlin-Brandenburg, 2025a, 2025b). In 2024, 19 hot days (temperature exceeding 30 °C) have been identified which is significantly more than the average of 13 hot days from 1985 to 2023 (Amt für Statistik Berlin-Brandenburg, 2025). A significant correlation has been found between hot days and mortality in Berlin (Amt für Statistik Berlin-Brandenburg, 2025a, 2025b).

To guide Berlin's path towards climate neutrality by 2045, StEP Climate 2.0 focuses on spatial and urban planning strategies/ measures to address climate change (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023). 24 exemplary climate protection and adaptation measures are integrated into neighbourhood concepts using 10 urban structure and area types (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023). Out of these, 5 urban structure types (USTs) encompassing residential use such as block development, high-rise buildings, row development, (semi-) detached and terraced houses and multi-family buildings (Fig. 3(a)) are the focus of this study. Heat-relevant characteristics such as green spaces and building density vary largely within these USTs (Battisti et al., 2019; Klopfer, 2023; Iqbal et al., 2025). Table A1 gives the characteristics, future potentials, priority measures and tools to implement UST tailored measures in Berlin based on Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen (2023).

Temporal analysis of population using demographic data (Amt für Statistik Berlin-Brandenburg, 2022) indicates that ~1.29 million residents (around one-third of Berlin's total population) live in block developments. The population density in these areas reaches 340 inhabitants per hectare, which is nearly eight times higher than Berlin's overall average of 42 inhabitants per hectare (Amt für Statistik Berlin-Brandenburg, 2022). Moreover, the population density within block structures has experienced a notable increase of 25 inhabitants per hectare over the decade from 2010 to 2021 (Fig. 3(b)). Similarly, multi-family buildings built after 1990 have also experienced a stark increase of population density over the same period. The difference in population density is 27 inhabitants per hectare from 2010 to 2021 and the population density is around 206 inhabitants per hectare in the year 2021. Conversely, a comparatively low population density of 164 and 46 inhabitants per hectare is found in row development and (semi-)detached and terraced houses, respectively, with small increases of 9 and 1 persons per hectare over 2010 to 2021.

3.2. Household survey

In October 2022, the households from about 10,000 residential addresses across 39 of Berlin's planning areas (PLRs: *Planungsräume;* Fig. 3(a)) were invited by post to participate in our survey. To capture diverse and representative sample of households and their living environment, 39 PLRs were selected based on stratified sampling through population density and age groups (Amt für Statistik Berlin-Brandenburg, 2022), unemployment levels (Senatsverwaltung für Stadtentwicklung und Wohnen, 2019), heat exposure (Senatsverwaltung für Wissenschaft, Gesundheit und Pflege, 2024) and heat-related mortality rates (Schuster et al., 2014). The posted invitations contained a QR code and password to access the online survey (Evasys GmbH, 2021). To ensure inclusivity, participants could also request a printed version of the questionnaire to be sent by post.

Filling the questionnaire required ~25–30 min. A broad range of topics such as living environment (e.g., building information, greenspace access), socio-demographic characteristics (e.g., age group, income and education), heat stress perception and experience to adaptation options and early warning systems, were covered. Measures encompassing behavioural adaptation as well as structural adaptation were also captured. Survey participants could indicate if structural measures have already been implemented, are already planned or considered as a future option or if they are considered neither today nor in future. Participants could also indicate whether a measure did not apply to their living environment. Seven cognitive pre-tests were used to refine the questionnaire.

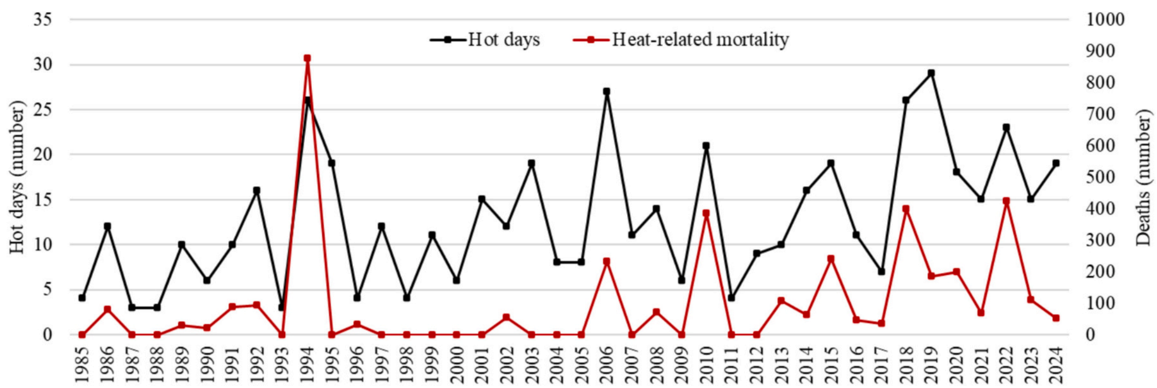

Fig. 2. Hot days and heat-related mortality in Berlin from 1985 to 2024 (data: Berlin Amt für Statistik Berlin-Brandenburg, 2025a, 2025b).

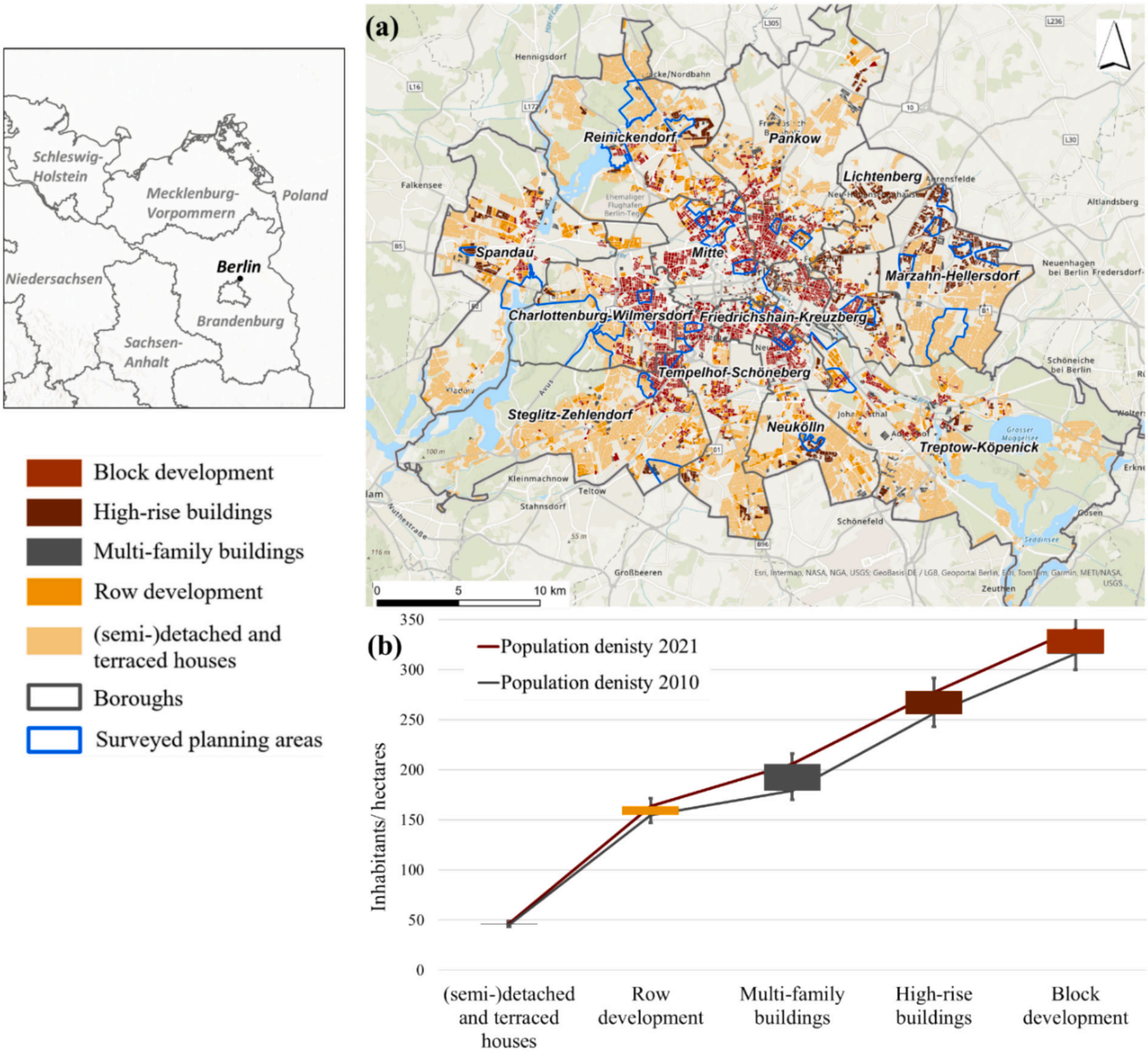

Fig. 3. (a) Surveyed planning areas and location of residential urban structure types (coloured) in Berlin boroughs (labelled) analysed in this study (data from Senatsverwaltung für Stadtentwicklung und Wohnen, 2021) and (b) population density (inhabitants per hectare) in Berlin USTs (coloured) in the year 2010 and 2021 (data: Amt für Statistik Berlin-Brandenburg, 2010, 2021).

We received a total of 569 completed questionnaires (response rate of ~6%), despite efforts to increase the respondent numbers, e.g., through press releases. A comparison between survey data and micro-census Berlin reveals the overrepresentation of high-educated households and underrepresentation of one person households (Table A2). Amongst gender, age groups, and household net income, the distribution of data is quite representative (Table A2). Given the scope of this paper, we use the survey topics related to the household behavioural and structural adaptation measures, living environment and socio-economic factors as presented in Table 1. Apart from household surveys, USTs in Berlin were acquired from Senatsverwaltung für Stadtentwicklung und Wohnen (2021). Population statistics at Block scale were collected from Amt für Statistik Berlin Brandenburg, 2022 for the year 2011 and 2021 to capture the temporal dynamics of population density amongst different USTs. The Urban Development Plan (StEP) Climate (Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen, 2023) and Heat Protection Plan (Senatsverwaltung für Wissenschaft, Gesundheit und Pflege, 2024) provides state of the art knowledge on target groups and areas in Berlin regarding heat adaptation.

3.3. Statistical analysis

Three analytical methods are used to answer the research questions on behavioural and structural adaptation measures: (i) descriptive statistics to study the implementation status of measures, (ii) cross tabulation and bivariate correlation analysis to investigate how measures differ amongst urban structure types and households' socio-economic profiles; (iii) regression analysis to determine factors influencing the decision to implement measures. Based on our conceptual framework, we developed six regression models. Three of these calculate whether the decision to implement structural adaptation measures is influenced by USTs, household socio-economic status or heat-specific adaptive capacity such as risk perception or awareness. The other three are used to explain whether physical and socio-economic or heat-specific adaptive capacities influence decisions on behavioural or non-structural adaptation.

3.3.1. Regression model and its evaluation

Adaptation measures are evaluated at different levels, starting from a binary (Yes/No) classification of the household's implementation status. Already implemented or planned measures are considered as taken adaptation measures. All taken adaptation measures are then grouped into two broader adaptation categories of structural and behavioural adaptation (Table 1). Adaptation intensity is calculated using the simple unweighted sum of adaptation measures that households have taken. We assume that each adaptation measure is equally important depending on the location where it is implemented. Lastly, the counts of structural and non-structural/behavioural measures serve as the dependent variables for the regression model. As the dependent variables are counted, we used a Poisson regression model (Nelder, 1974). The Poisson regression model is calculated by:

$$\log(\lambda i) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots$$

λi denotes the expected count of structural and behavioural adaptation measures adopted by the i-th household. Xi is a matrix of

Table 2
Summary statistics.

Explanatory variables	Variable type	Median	Mean	SD	Minimum	Maximum
Urban structure type	Nominal 1 = Block development; 2 = High-rise buildings; 3 = Multi-family buildings 4 = Row development; 5 = (semi-)detached and terraced houses	–	–	–	–	–
Building age	Ordinal	8 – 1960–1969	8.05	4.24	1 – before 1900	15 – 2020–to date
Renovation/renewal	Binary	1 – yes	0.75	0.43	0 – no	1 – yes
Respondent age	Ordinal	4 – 45–54 years	4.29	1.69	1 – 18–24 years	8 – 85 years and above
Household size	Ordinal	2 – 2 persons	2.08	0.94	1 – 1 person	5 – More than 4 persons
Ownership status of the residence	Dummy takes the value 1 if the dwelling is owned otherwise it takes 0	0 – rented dwelling	0.25	0.43	0 – rented	1 – owned dwelling
Approximate net monthly household income	Ordinal	10 – 3600 to under 4000 €	9.58	4.33	1 – less than 900 €	16 – More than 7000 €
Willingness to pay for structural measures	Binary	1 – yes	0.57	0.50	0 – no	1 – yes
Highest educational qualification of household	Ordinal, ranked based on education level	6 – university degree	5.27	1.40	1 – secondary education degree (after 8 or 9 years) *	6 – university degree
Duration of residence	Continuous	2009	2009	–	1940	2022
Support from neighbours (e.g., in case of medical emergency)	Ordinal	2 – supportive	2.24	1.23	1 – very supportive	4 – not supportive
Perceived heat stress risk in the residence	Ordinal	2 – slightly cooler	2.54	1.22	1 – very cool	5 – very hot
Experience with the impacts of heat stress on daily routine	Binary	1 – yes	0.65	0.48	0 – no	1 – yes
Knowledge about early-warning systems	Binary	1 – yes	0.89	0.31	0 – no	1 – yes
Expectations towards authorities e.g., subsidies	Binary	1 – yes	0.76	0.43	0 – no	1 – yes
Knowledge on self−/ household protection measures against heat stress	Binary	1 – yes	0.80	0.40	0 – no	1 – yes
Perceived ability to protect the residence against heat stress	Binary	1 – yes	0.66	0.48	0 – no	1 – yes
No of structural measures implemented	Continuous	2	2.85	1.76	0	8
No of non-structural/ behavioural measures implemented	Continuous	6	6.11	1.84	0	11

Missing values are excluded from the regression model.

* 'Hauptschulabschluss' / 'Volksschulabschluss'. Lowest level of secondary degree education in Germany.

covariates comprised of explanatory variables which influence a household's decision regarding adaptation choices. In this case, these are the indicators of households' general adaptive capacity and heat-related adaptive capacity presented in Table 1. β is a matrix of regression coefficients to be estimated. In the Poisson model, the stochastic uncertainty component is incorporated through the assumption that the dependent variable follows a Poisson distribution with mean λi, therefore, no separate additive error term is specified (Nelder, 1974). Before examining the determinants of adaptation actions at household scale, the specifications of the Poisson loglinear model are tested against alternative models to evaluate its suitability. First, the Poisson loglinear model is compared with the negative binomial regression model (Long and Freese, 2006). The significant dispersion parameter indicates no over-dispersion or zero-inflation in the data, suggesting adequate observed heterogeneity amongst observations and supporting the use of the Poisson loglinear model. Subsequently, the two-stage hurdle model is tested against the single-stage Poisson loglinear model regression using a likelihood ratio (LR) test (Greene, 2003), given that the Poisson loglinear model is nested within the double hurdle framework. Poisson loglinear models support different data types, therefore, independent variables are both ordinal and nominal. However, to facilitate the analysis we built the binary variables for some independent variable e.g., ownership status and building renovation/renewal etc. as presented in Table 2.

4. Results

4.1. Status of household-scale heat adaptation measures in Berlin

The findings of the descriptive statistics indicate that most households in the study area have implemented both structural and behavioural adaptation measures. However, behavioural measures have generally wider implementation levels amongst survey respondents (Table 2).

On average, households conducted more than two structural adaptation measures (mean = 2.85, SD = 1.76), with the number of measures ranging from 0 to 8, out of a total of 10 locally diversified practices presented in Table 2. Only 4% of the sample reported not having adopted any structural measure. Amongst heat-related structural adaptation, the reported planned or implemented options vary considerably by type of measure. Cross ventilation of the dwelling is the most practised measure implemented by 84% of respondents. Next to that, shading and planting/trees/water areas are reported to be planned or implemented by 42% and 43%, respectively. Measures constituting climate-optimization in the building such as insulation and using high-albedo exterior surfaces (paints, coatings), e.g., on the sun exposed side of buildings, are planned and implemented by 22% and 23% of respondents, respectively, while heat-proof windows/frames for solar control are implemented by 20% of respondents. Amongst structural adaptation measures the least planned or implemented measures are green roofs, green façades and air-conditioning reported by only 3%, 5% and 7% of participants, respectively, potentially due to tenure type, space constraints, higher installation costs or lower perceived necessity. It should be noted that amongst the structural measures such as heat-proof windows/frames, high-albedo building coatings, insulation and green roofs or façades, more than half of respondents reported ‘does not apply.’ Further analysis revealed that 74% of those respondents reside in block developments or high-rise buildings, and 84% are tenants. These factors likely constrain their ability to implement certain measures, particularly those requiring significant modifications of the building's exterior.

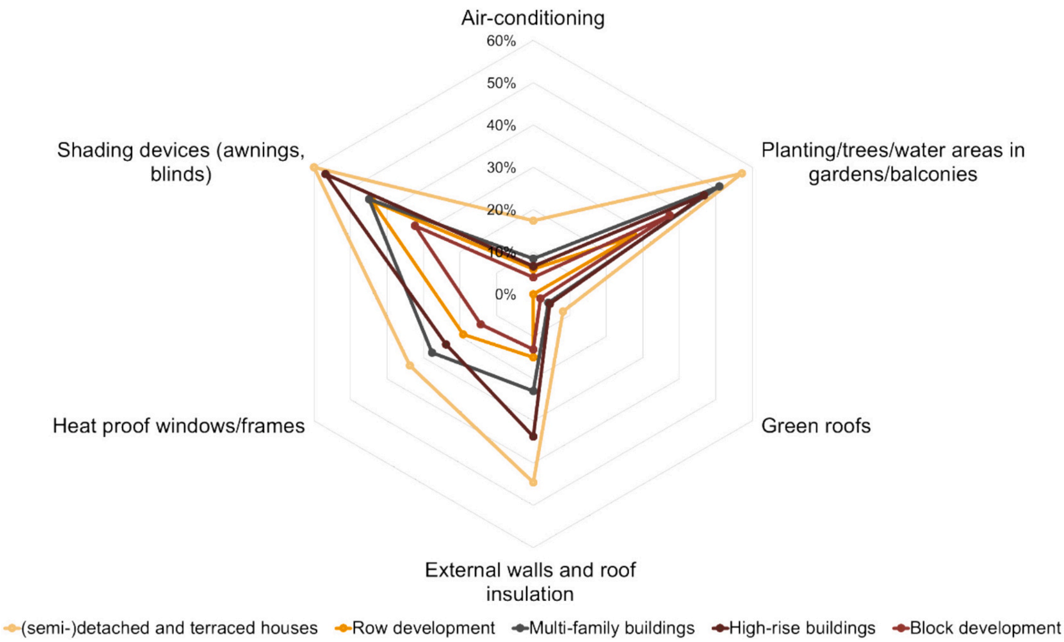

Fig. 4. Planned or already implemented adaptation measures as percentage of survey respondents in different USTs (line colours).

Overall, respondents have adopted more than 6 behavioural heat adaptation measures on average (mean = 6.11, SD = 1.84) with the number of measures ranging from 0 to 11 out of 12 choices (Table 2). Next to increasing water intake (reported by 94% respondents), ventilation at night or during early mornings and avoiding outdoor heat exposure are amongst the highly implemented behavioural measures. To reduce overheating in the building, 87% of respondents ventilate their dwelling at night or in the morning and 78% keep windows and shutters closed during periods of high insolation during the day. Amongst the respondents, 82% avoid visiting densely built-up places that offer little shade during hot hours, e.g., the city centre or the main street, and 65% visit cooler places outside like parks, forests or outdoor swimming pools. 66% of respondents avoid heat exposure by limiting their activities to mornings or evenings. Due to previous experience with excessive indoor heat, 8% of respondents have already relocated to a heat-adaptive dwelling with good ventilation and lots of green spaces and 6% of respondents selected a heat-adapted living environment/neighbourhood with sufficient cold air supply and green spaces. Interestingly, 20% of respondents selected a heat-adapted workstation featuring adequate shading and good ventilation.

4.2. Variability of implemented heat adaptation measures by USTs

Results of bivariate correlation between structural adaptation measures and USTs ($r = 0.280$, $p = 0.01$) show a statistically significant positive association. Opposite to this, perceived heat stress in the residence is significantly but negatively associated with USTs ($p = 0.01$, $r = -0.18$). This inverse relationship points out to the gap between implemented adaptation measures and highly exposed USTs in terms of perceived heat stress. This paradox is further discussed in Section 5.2.

The comparison across USTs indicates that a higher percentage of planned and implemented adaptation measures are reported in low-density USTs compared to those in high-density USTs (Table 2, Fig. 4). On average, two structural measures are planned or implemented in the block development UST while the result is four structural measures for (semi-)detached and terraced houses. 32% of respondents in block developments have planned or implemented shading (e.g., awnings or blinds) compared to 60% of respondents in (semi-)detached and terraced houses. Likewise, 32% more respondents in (semi-)detached and terraced houses have planned/implemented insulation than those living in block developments. Interestingly, high-rise and multi-family buildings reported better implementation of measures such as planting/trees/water areas (47% and 51%, respectively) and shading (57% and 45%, respectively) than block development (planting: 37% and shading: 32%). However, low implementation levels are reported for green roofs and air conditioning regardless of UST. Implementation status differences of measures across USTs depend significantly on type. For instance, implementation of planting, green roofs and air conditioning does not considerably differ across USTs. On the other hand, shading, insulation and heat-proof windows/frames implementation considerably differ amongst USTs. The results suggests that households in lower-density environments e.g., (semi-)detached and terraced houses, seem to have more options and resources to implement heat adaptation measures. Moreover, there is a statistically significant correlation ($r = 0.388$, $p = 0.001$) amongst USTs (order given in Table 2) and ownership status of building which impacts the capacity for implementation as well as the willingness to pay for structural measures (Fig. A). This aspect is further discussed in Section 4.3.

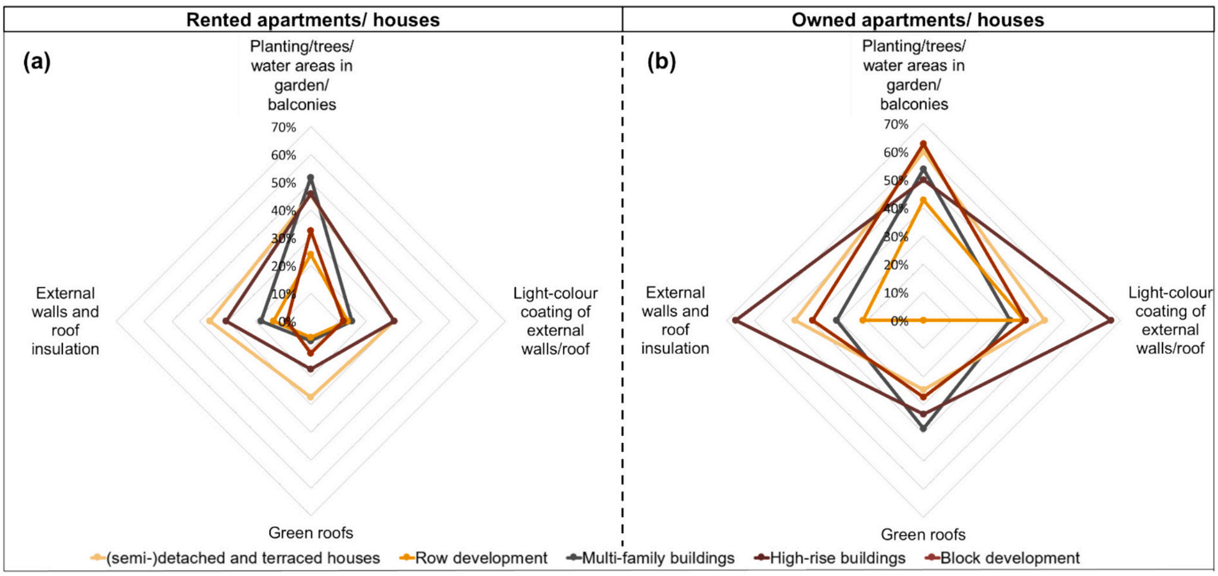

Fig. 5. Planned or already implemented adaptation measures as percentage of survey respondents who are (a) renters or (b) owners living in different USTs (line colours).

4.3. Variability of implemented heat adaptation measures by building tenure

Building tenure significantly affects the implementation of heat-related structural adaptation measures ($r = 0.36$, $p = 0.001$). Overall, ownership of the dwelling increases the potential of structural adaptation by 50% (Fig. 5). In case of rented dwellings (Fig. 5a), there is a lower level of planned or implemented measures compared to dwellings that are owned (Fig. 5b), with some USTs such as (semi-)detached and terraced houses and high-rise buildings achieving much higher percentages of responses, suggesting greater adaptation engagement. In particular, substantial differences are observed in specific measures such as planting/trees/water areas which 58% of owners have planned or implemented compared to only 35% of renters. Similarly, 41% of owned dwellings have (or are planned to have) some form of insulation, compared to only 16% of rented dwellings.

In certain USTs, the disparity between owners and renters in the planning or implementation of heat adaptation measures is particularly pronounced. For instance, in block developments, 39% of owners have insulation, compared to only 9% of renters. Similarly, in high-rise buildings, 67% of owners have implemented light-coloured painting or shading elements on sun-exposed façades, compared to 30% of renters. In row housing developments, 69% of owners have installed shading devices such as awnings or blinds, in contrast to 39% of renters. There is a statistically significant positive ($r = 0.21$, $p = 0.01$) correlation between ownership status and willingness to pay for structural measure (Fig. A), underscoring the critical role of ownership in facilitating long-term investments in the built environment.

4.4. Variability of implemented heat adaptation measures by age group

Mixed results have been reported amongst age groups regarding the implementation of structural and behavioural adaptation measures. Overall, age-related adaptation decisions of the households are driven by their specific heat-related adaptive capacity reflected in form of their willingness to pay for structural measures ($r = 0.105$ and $p = 0.034$), preparedness ($r = 0.187$, $p = 0.001$), ownership status ($r = 0.262$, $p = 0.001$) and duration of residence in the same dwelling ($r = 0.460$, $p = 0.001$; Fig. A).

On average, structural adaptation measures are highly reported amongst the age group of 45–64 year olds and ≥ 75 years which presents the positive role that age can play in promoting structural adaptation due to, e.g., ownership and duration of residence. Measures such as shading devices, planting/trees/water areas and building insulation are planned or implemented by 60%, 53% and 27% of elderly ($\geq$75 years) compared to 27%, 18% and 18% of younger people (18–24 years). For certain measures, e.g., installing heat-proof windows and potential to cross-ventilate, the intention to adapt either remains constant or drops above a certain age threshold (45–64 years) showing limited household willingness to implement structural adaptation. Overall, the youngest age group surveyed (18–24 years) have planned/implemented the least structural adaptation measures (Fig. 6).

In terms of non-structural adaptation measures, the intention to adapt overall increases until the age range of 45–64 years and then it drops. Fig. 6 presents that behavioural adaptation such as avoiding hot places and visiting cooler places is reported more frequently

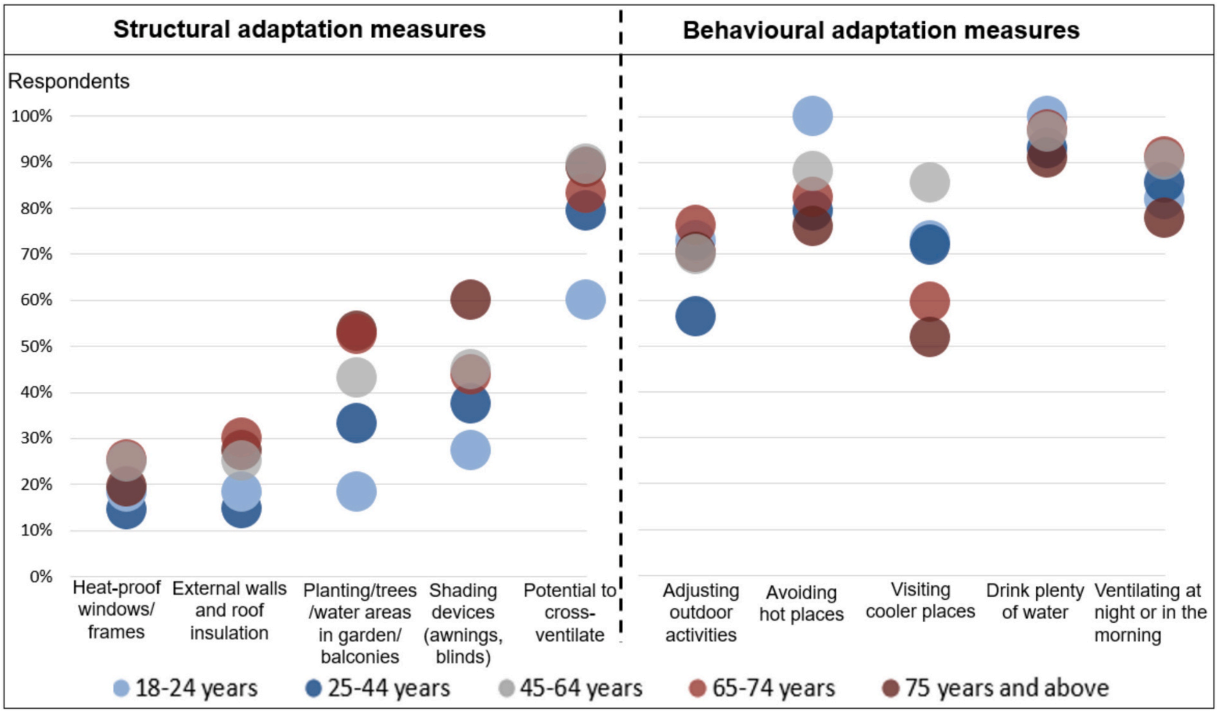

Fig. 6. Planned/implemented adaption measures (structural or behavioural) as percentage of survey respondents grouped by age cohorts (colours).

(100% and 73%, respectively) amongst the younger respondents (18–24 years) compared to the elderly (76% and 52%, respectively). In some cases, working-age adults (25–44 years) are less flexible, i.e., only 56% reported to move their outdoor activities to the mornings or evenings, compared to >70% for other age cohorts. Interestingly, the potential to cross-ventilate the dwelling does not translate directly into ventilation effort: Out of approximately 90% of elderly respondents (≥70 years) only 78% are able to ventilate their dwelling at night or in the morning due to reduced mobility or health conditions.

4.5. *Variability of implemented heat adaptation measures by household income groups*

Income levels influence the type and extent of both structural and non-structural heat adaptation measures (Fig. 7). At the household scale, income-related adaptation decisions appear to be shaped by the household's generic adaptive capacity, e.g., ownership status ($r = 0.344$, $p \leq 0.001$) and heat-related adaptive capacity, particularly the willingness to pay for structural measures ($r = 0.240$, $p \leq 0.001$; Fig. A).

Higher-income households are more likely to implement structural adaptation measures such as shading devices: 47% of respondents in the higher income group (>EUR 4000) reported installing them compared to 35% of respondents in the low-income group (<EUR 1300). Cross-ventilation potential in the building also differs significantly amongst income groups, with 28% more respondents from higher income groups being able to cross-ventilate their dwelling, compared to low-income groups. The prevalence of air-conditioning is very low overall, with only small differences amongst income groups. For other measures, including improved insulation and heat-proof windows, observed differences are also minor (Fig. 7).

Lower-income households show a higher prevalence for behavioural adjustments such as changing the timing of outdoor activities (71% of respondents). However, avoidance of heat exposed locations in favour of cooler/shaded outdoor environments is more common amongst the higher or middle-income groups. Differences in the implementation of other measures, such as ventilation behaviour, are relatively small. Although these findings highlight the marginal role of economic capacity in determining adaptive choices, the need for targeted interventions to support heat resilience amongst lower-income groups is evident.

4.6. *Factors influencing implementation of heat adaptation measures*

Poisson regression explains the influence of urban form and socio-economic structure on the number of planned and implemented structural and behavioural heat adaptation measures (Fig. 8). In terms of generic adaptive capacity, UST is a significant predictor of the number of planned/implemented structural adaptation measures. Compared to the (semi-)detached and terraced houses, the number of structural adaptation measures is reduced by a factor of 0.639 (95% CI (confidence interval) = 0.534–0.765) in block developments,

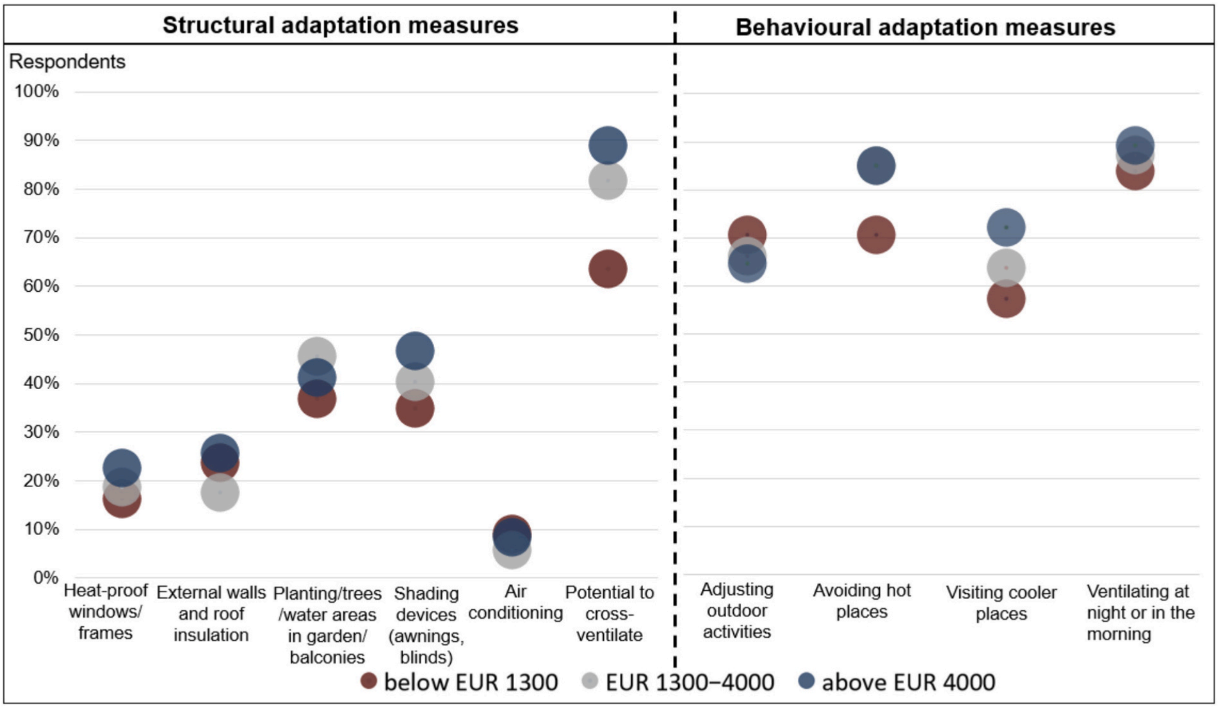

Fig. 7. As Fig. 6 but classified household income groups (colours). Based on households equalised disposable net income, three income groups can be defined as: low income <€1300, middle income €1300–€4000, and high income >€4000. These correspond approximately to 15%, 70%, 85% quantiles of micro census Berlin (2022). Income is the household's disposable monthly net earnings after tax and social security deductions.

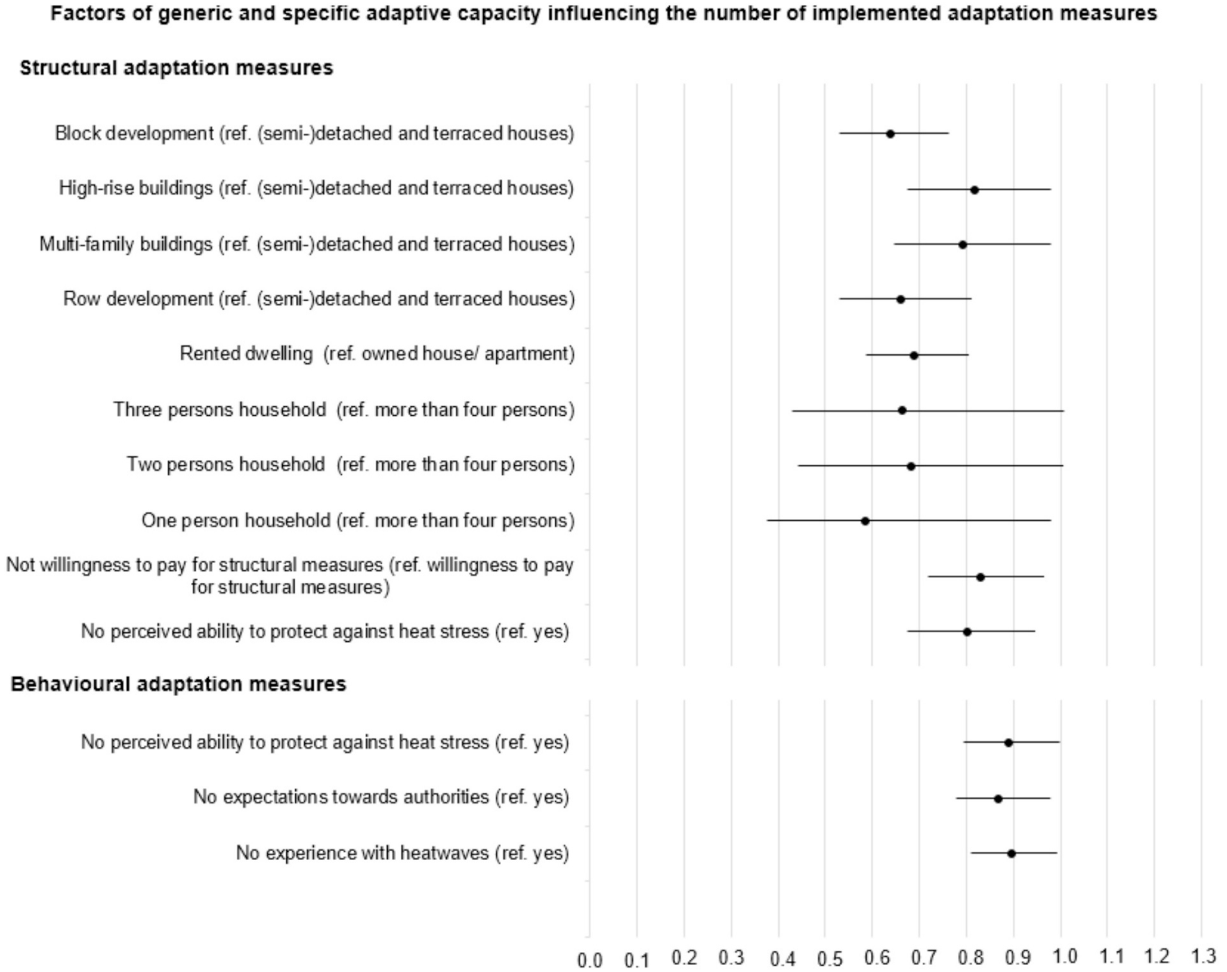

Fig. 8. Forest plot explaining the results of Poisson regression modelling to summarize the factors influencing the number of implemented heat-related structural and behavioural adaptation measures (Table A3). The exponentiated values of coefficients (Exp(B)) and 95% confidence intervals (CI) are represented. In the case of categorical variables, the reference groups are depicted in brackets. Statistically significant estimated coefficients are given in Table A3.

ceteris paribus (c.p.), a statistically significantly result ($p < 0.0005$). Building age seems to be non-influential in the model probably due to building retrofitting measures.

Regarding socio-economic variables, building tenure, household size and household willingness to pay for structural measures can significantly predict the implementation status of structural adaptation. For rented dwellings, the number of implemented structural adaptation measures is reduced by a factor of 0.688 (95% CI = 0.582–0.814 and $p < 0.0005$) compared to owned dwellings, c.p. Household size also plays a significant role in implementation of structural adaptation measures. The regression coefficient decreases to 0.585 in case of a single person household (95% CI = 0.377–0.907, $p = 0.017$) indicating a decline of ~52% in the implemented structural measures, c.p. However, the coefficient interval is rather wide indicating higher uncertainty (Fig. 8). Contrary to income, for which the influence is rather insignificant in the model, willingness to invest in structural measures significantly ($p = 0.012$) influences the implementation status of adaptation measures. If the household is not willing to invest in structural adaptation measures, expected implemented measures will reduce by a factor of 0.831 (95% CI = 0.719–0.960).

Specific heat-related adaptation capacity indicators such as perceived heat stress, knowledge about early-warning systems and expectations towards authorities are not significant predictors. However, the household's perceived ability to protect their residence against heat stress is a significant predictor ($p = 0.010$). Households that perceive themselves as unable to protect their residence against heat stress, on average, implement 0.802 fewer structural adaptation measures (CI = 0.678–0.949), c.p. Therefore, awareness about the ability to act is a clear precondition for implementation.

On the other hand, urban form and socio-economic status seemed to have insignificant influence on non-structural heat adaptation measures. We have found three significant predictors of non-structural adaptation measures related to heat-specific adaptive capacity. The first one is experience with heat stress. Households that perceived little effects of heat stress on daily activities implement 0.895 fewer non-structural adaptation measures (CI = 0.809–0.992, $p = 0.03$), c.p. The second one is expectations towards authorities, e.g., in form of subsidies to address heat stress. Households that do not expect to receive government funding for adapting, also implement 0.868 fewer non-structural heat adaptation measures (CI = 0.777–0.970, p = 0.012), c.p. The third significant predictor ($p = 0.046$) is perceived ability to protect against heat stress. Those households which perceive themselves to be unable to protect themselves against heat stress, on average, implement 0.890 fewer behaviour adaptation measures (CI = 0.793–0.998), c.p. This further emphasizes that awareness of the capacity to act serves as a key prerequisite for effective implementation.

5. Discussion

Urban areas are heterogeneous with varying physical and socio-economic characteristics. By focusing on heat-related adaptation measures implemented in Berlin and its linkages with urban structure types and socio-economic profiles of people, the study recognizes that effective climate adaptation planning requires comprehensive understanding of different physical and social characteristics of neighbourhoods and the willingness and options to adapt by different social groups. Correlation and regression analysis provide a robust quantitative basis to better understand these linkages.

5.1. Socio-physical dimension of structural and behavioural adaptation

Overall, survey participants reported implementing non-structural adaptation measures approximately three times as often as structural ones. The study reveals that individuals most commonly begin to mitigate impacts of heat stress at the personal scale, e.g., though ventilating the residence during cooler hours and keeping windows and shutters closed during the day, adjusting behavioural patterns (e.g., avoidance of heat-exposed areas, temporal limitation of outdoor activities) and increased water intake (Section 4.1). Poisson regression indicates that these non-structural adaptation measures are influenced by heat-specific adaptive capacity of households as explained by Eakin et al. (2014) such as previous experience with heat stress, expectations towards authorities and preparedness to cope with hot days (Section 4.6). When households perceive that an increase in temperature is affecting their daily routines and have knowledge of self−/household protection against heat stress, they tend to implement more non-structural adaptation measures. Meta analysis of the literature also confirms the positive influence of prior heat stress experience and preparedness on adaptation behaviour (Elrick-Barr et al., 2014; Nhuan et al., 2016; Otum Ume et al., 2020; Beckmann et al., 2021b; Ahmed et al., 2025b; Schubert et al., 2025). However, lack of expectations, e.g., in form of subsidies to address heat stress, has a negative influence. This result supports conclusions by Mortreux et al. (2020) that a lack of trust in authorities can reduce the uptake of basic preparatory measures advised by authorities. Similarly, Otum Ume et al. (2020) showed that lack of government support can lead to refusal of climate change adaptations amongst households.

Non-structural adaptation often extends to structural measures, i.e., from personal adjustments and behavioural adaptation to changes of the living environment (e.g., Ahmed et al., 2025b). Amongst structural adaptation measures, installing shading devices and planting are the most commonly reported measures followed by building insulation, painting light colours and heat-proofing windows (Section 4.1). Poisson regression shows that USTs and household socio-economic profiles like ownership status, household size and willingness to implement measures shape a household's decisions on structural adaptation (Section 4.6). In terms of living environment, it is found that in low-density USTs (e.g., (semi-)detached and terraced houses) implementation levels of structural adaptation measures are twice as high compared to high-density USTs like block developments. Studies by Iqbal et al. (2025) and Klopfer (2023) found similar differences linked to vegetation fraction (including trees) in different Berlin USTs, but with impact on neighbourhood-scale adaptation rather than building-scale. In terms of building tenure, owners often have better control over their adaptation choices compared to renters, enhancing their ability to implement structural measures particularly related to climate optimization of the residence by insulation and building envelope coatings (Fig. 3). Ahmed et al. (2025b) and Schubert et al. (2025) highlighted disparities in adaptation amongst owners and renters in the European context.

The study also shows that the impact of age and income on shaping the adaptation actions is quite complicated. While structural adaptation increases with age up to late adulthood, non-structural and behavioural measures are more prevalent amongst younger people (Section 4.5). Overall, physical and financial capacity, mobility, and lifestyle flexibility collectively shape age-related adaptation behaviour. Economic capacity determines adaptation choices to a certain extent with wealthier households more often implementing structural measures (higher fraction of owners, higher willingness to invest in adapting their home), while lower-income groups are more dependent on behavioural strategies such as ventilation and altering of activity patterns. However, the marginal effect of income is diminished in the regression model due to other control variables such as ownership, household size and household willingness to pay for structural adaptation measures. Osberghaus and Abeling (2022) found in the German context that income is not a constraining factor for those households in need of heat adaptation. Similarly, Schubert et al. (2025) indicated the insignificant effect of household income on adaptation actions. Therefore, in terms of policy implications, renters and single-households need attention. Similarly, risk awareness can increase the self-efficacy and willingness of a household to implement measures.

5.2. Paradox between required and implemented measures

On average, the survey participants reported that structural adaptation measures are implemented twice as often in (semi-)detached or terraced houses than in block developments. However, block structures are mostly found close to the city centre (Fig. 2) and often highly exposed to heat (GEO-NET, 2014), which leads to a higher level of perceived heat stress in these households (Klopfer, 2023; Iqbal et al., 2025). Thus, for this UST our results have captured a dichotomy between the planned/implemented structural adaptation measures and exposure to heat stress. Looking at the population dynamics, close to 1.29 million people live in this structure type, accounting for a third of Berlin's total population (Amt für Statistik Berlin-Brandenburg, 2022). At 340 inhabitants per hectare the population density in the block structure UST is ~8 times higher than the Berlin-wide average of 42 inhabitants per hectares (Amt für Statistik Berlin-Brandenburg, 2022). Between the years 2011 to 2021, there also has been a substantial increase in the population density by 25 inhabitants per hectare (Fig. 3). The higher exposure and perceived heat stress as well as population density highlights the necessity for prioritizing adaptation actions in block developments.

A significant influence of household size in the Poisson regression model indicates that the probability of implemented structural measures is approximately 58% lower in one-person households than for couples and families (Section 4.6). According to the Berlin statistical office, 53.9% of households in 2022 were one-person households (Amt für Statistik Berlin-Brandenburg, 2022). Fig. 6 indicates the low preparedness and reduced willingness to pay for structural measures in younger age groups (18–24 years), which mostly live in single households. Therefore, lack of adaptive capacity and fewer implemented measures are observed amongst the younger age group compared to other age groups. Sandholz et al. (2021) found that people living in single person households such as students and young professionals are at higher risk due to their higher exposure and low adaptive capacity. Moreover, 24.6% of young adults aged 18 to 24 were most at risk of poverty in 2022 (Amt für Statistik Berlin-Brandenburg, 2022). These disparities underline the need for targeted support to enhance heat resilience amongst single person households and younger age groups.

5.3. *Study limitations and scalability*

Household survey studies exhibit inherent limitations in their scope and representation. In this study, one third of respondents were renters. While this is in line with household tenancy statistics in Berlin (85% renters; Amt für Statistik Berlin-Brandenburg, 2022), it may have influenced the types and extent of adaptation measures reported. While the survey has captured adaptation measures undertaken at the building-scale and represents household-level adaptation efforts, it provides limited insights into adaptation measures implemented at the neighbourhood scale. The latter include surface unsealing, planting in the neighbourhood, communal greening efforts, and wind corridor preservation as indicated under Urban Development Plan (StEP) Climate 2.0, 2022 (Table A2) by the Senate Department for Urban Development, Building and Housing. Moreover, collective or community-level initiatives, as well as macro-scale interventions such as access to cooling centres led by the municipality, are not captured. One of the methodological limitations is the use of an unweighted sum of adaptation measures in the correlation analysis and regression model. It may not accurately reflect the relative importance or contribution of different measures to overall adaptation actions. Future research could refine this approach by applying objective weighting methods, such as those derived from principal component analysis (Jolliffe and Cadima, 2016) or expert judgement. Furthermore, this study did not assess the effectiveness or the associated costs and benefits of specific adaptation measures, highlighting the need for future investigations in this area.

The insights from this study are not only valuable for Berlin but also serve as a model for other cities with similar challenges. The selection of explanatory variables, however, vary in different contexts. It would be interesting to apply this method to other case studies with diverse physical and socio-demographic structures to find similarities and differences of implemented adaptation measures and influential factors in different urban settings. The study also highlights the importance of identifying underlying factors driving human vulnerability and adaptive capacity to improve the implementation of adaptation strategies beyond conventional physical typologies and heat exposure levels.

6. Conclusion

Drawing on statistical data, physical urban structure and a household survey in Berlin, we systematically assessed the implementation of structural and behavioural adaptation measures and their link to the living environment and socio-economic characteristics of households. The main results can be summarized as follows: residents in denser block structures lack the adaptive capacity to implement structural measures which is embedded in the significant influence of ownership determining the willingness and potential to implement adaptation measures. To a certain extent, income plays a role in the implementation of heat adaptation measures, however, other control variables such as duration of residence and willingness to invest money in structural adaptation dominate. Tenants report a lack of adaptive capacity and limited implemented measures potentially reflecting low consideration of heat adaptation in the rental housing markets. We found that younger age-groups and those living alone do not have enough adaptive capacity and are more unwilling to implement structural measures (Fig. 6). Overall, structural heat adaptation measures are influenced by the living environment, i.e., urban structure types, ownership, household size, and household willingness to implement structural measures while behavioural adaptation is influenced by past experiences, expectation towards authorities and the household's perceived ability to protect against heat stress. Thus, the study underscores that adaptation measures cannot solely be defined by looking at differentiated exposure levels or physical urban structure types as often done, but need to better capture and understand adaptive capacities and the level of planned and already implemented structural and non-structural adaptation measures along different USTs and social groups.

To tackle excessive heating, the Senate Department for Science, Health and Care and State Office for Health and Social Affairs Berlin (2024) under the Heat Protection Plan have actively provided advice to residents on precautionary measures. Targeted advice is provided in different languages to vulnerable groups such as elderly, people with chronic illnesses, the homeless, outside workers and families with children (Senatsverwaltung für Wissenschaft, Gesundheit und Pflege, 2024). Our analysis also underscores the need for considering more precisely how to reach different population groups for strengthening heat adaptation. In this regard, awareness campaigns should inform susceptible households in particular to build self-efficacy regarding adaptation measures. Moreover, rental housing markets should prioritize adaptation to heat stress in the existing and new housing stock. Often, housing companies dealing with social housing encounter financial constraints. Therefore, incentives and subsidies can support them to implement planned adaptation measures. Municipalities in Berlin under the heat protection plan (Senatsverwaltung für Wissenschaft, Gesundheit und Pflege, 2024) have mapped drinking fountains, shaded places and water areas. Moreover, designated cool rooms in communal settings like churches, neighbourhood meeting points or senior citizen centres are set up during hot days. Exposed neighbourhoods and USTs should be given a priority in future initiatives aimed at improving community heat resilience.

Beyond its direct findings, the methodological approach employed in this study offers transferable insights for other regions facing similar heat-related risks. The structured integration of behavioural and structural adaptation with the physical and social urban structure provides a replicable framework that can be adapted to different geographic and socio-economic contexts. However, while the approach provides a strong foundation at micro (household) scale, future research should incorporate meso- (e.g., neighbourhood-level) and macro- (e.g., municipality-level) scale interventions and their linkage with socio-physical urban structure to draw a comprehensive understanding of adaptation actions across scales.

CRediT authorship contribution statement

Nimra Iqbal: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Joern Birkmann:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Marvin Ravan:** Writing – review & editing, Project administration, Data curation, Conceptualization. **Denise Hertwig:** Writing – review & editing. **Sarah Lisa Mack:** Writing – review & editing. **Maximilian Rembold:** Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Additional information

Table A1
Profiling of USTs based on the Urban Development Plan Climate 2.0 by Senatsverwaltung für Stadtentwicklung, Bauen und Wohnen (2023).

Type	Characteristics	Transition	Future potentials	Measures	Tool
Block development	Wilhelmina period. Closed row along streets. Predominantly residential, with shared courtyards.	Interior areas converted into green spaces and car parking; low buildings replaced by higher ones; attics/buildings extended	Block edge development can be densified	Removing sealing and adding courtyard greenery, ventilation, energy retrofitting, solar panels, shaded seating, etc.	Green roof funding programs; collaboration between neighbours to implement comprehensive measures.
High-rise buildings	Extensive residential zones with open spaces	Some renovated in 1990s to improve energy efficiency	Blue green adaptation in the open spaces between buildings, Green roofs partial desealing, Solitary trees	Redesign of open spaces for recreation and water retention, community energy systems.	Cross property concepts for heat protection and greening
Multi-family buildings	Built with energy-saving, ecological principles. Compact city location, green roofs, rainwater infiltration, passive housing. Semi-public green spaces and playgrounds.	Solitary and peripheral buildings, densifying single-family housing areas.	Densifying low-story plots, extending roofs, and converting open spaces to blue and green infrastructure	Rooftop solar panels, thermal retrofitting, communal green areas.	Public-private collaborations for implementing neighbourhood-wide measures.
Row development	Housing from 1920s–1930s, aligned at right angles to the street. Linear blocks with open	Rows not necessarily perpendicular to streets	Densifying low-story plots, extending roofs, and converting open	Shading, rainwater harvesting, wind corridor preservation, shade-	Public-private collaborations for

(continued on next page)

Table A1 (*continued*)

Type	Characteristics	Transition	Future potentials	Measures	Tool
	spaces between buildings. East-west orientation.		spaces to blue and green infrastructure	providing trees, and green roofs on large flat roofs.	neighbourhood-wide measures.
(semi-)detached and terraced houses	Low-density housing with individual gardens.	Division of plots to build on green interior areas	Densification by adding floors/ extending roof	Tree planting, permeable surfaces, and renewable energy integration. Preserving wind corridors	IBB funding programs for modernization and energy efficient building

Table A2
Comparison of Berlin's micro-census data (2022) with the socio-economic sample characteristics.

Socio-economic characteristics	Micro-census 2022	Household survey Berlin 2022
Age groups		
18–24 years	8.6%	1.9%
25–44 years	38.4%	35.3%
45–64 years	30.3%	35.3%
65–74 years	10.9%	17.9%
75 years and elder	11.8%	9.6%
Gender		
Male	51.10%	53.4%
Female	48.90%	45.5%
Divers	–	1.1%
Household size		
1 person	53.9%	26.7%
2 persons	26.2%	49.8%
3 persons	9.8%	7.1%
4 persons and more	10.1%	2.1%
Household net monthly income		
Low (below EUR 1300)	14.8%	13.7%
Middle (EUR 1300–4000)	57.6%	44.6%
High (above EUR 4000)	27.6%	41.7%

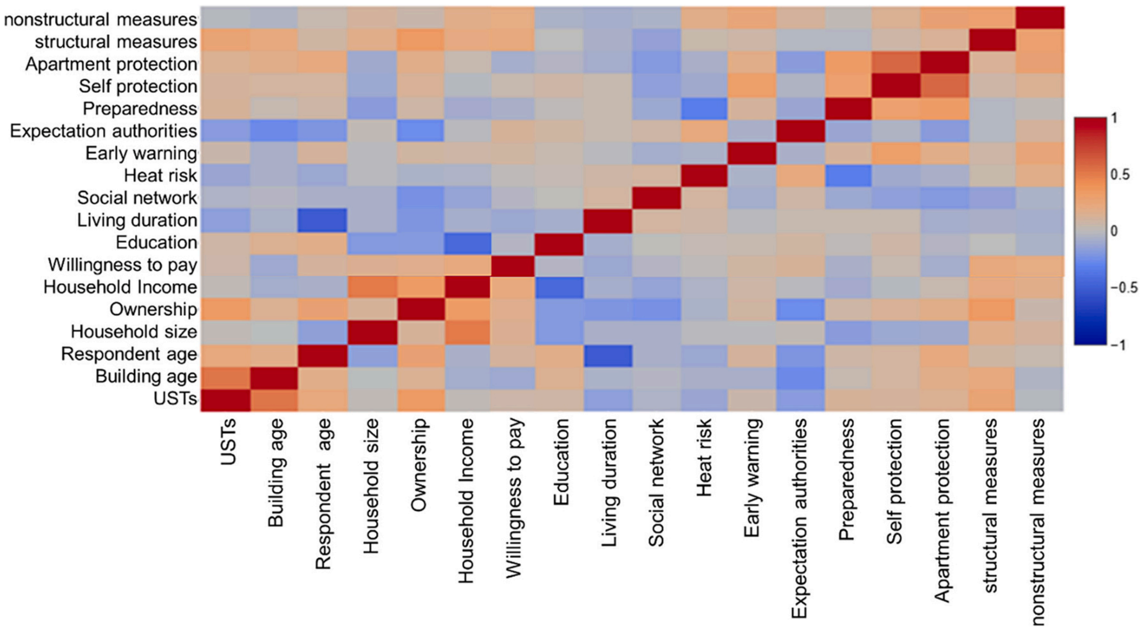

Fig. A1. Heat correlation map showing bivariate association between indicators of adaptive capacity and adaptation measures. Colours indicate the strength and direction of the association (red: positive relationship, blue: negative relationship; range: −1 to +1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table A3
Results of the Poisson regression model explaining the number of heat-related structural and behavioural adaptation measures implemented. The

coefficient estimates (B), statistical significance (p), exponentiated values of coefficients (Exp(B)) and 95% Wald Confidence Interval (CI; (Wald, 1949)) for Exp(B) are given.

Explanatory variables	B	p	Exp(B)	95% Wald Confidence Interval for Exp(B)	
				Lower	Upper
Structural adaptation measures					
Urban structure types					
Block development	−0.448	<0.0005	0.639	0.534	0.765
Large housing estate	−0.203	0.025	0.816	0.684	0.975
Multifamily buildings	−0.233	0.034	0.792	0.638	0.983
Row development	−0.416	<0.0005	0.659	0.535	0.812
(semi-) detached and terraced houses	0[a]		1		
Household size					
One person household	−0.536	0.017	0.585	0.377	0.907
Two persons household	−0.380	0.084	0.684	0.445	1.052
Three persons household	−0.409	0.075	0.665	0.424	1.043
Four persons household	−0.225	0.343	0.799	0.502	1.271
More than four-person household	0[a]		1		
Building tenure					
Rented dwelling	−0.373	<0.0005	0.688	0.582	0.814
Owned dwelling	0[a]		1		
Willingness to pay for structural measures					
No	−0.185	0.012	0.831	0.719	0.960
Yes	0[a]		1		
Perceived ability to protect against heat stress					
No	−0.220	0.010	0.802	0.678	0.949
Yes	0[a]		1		
Behavioural adaptation measures					
Experience with heatwaves					
No	−0.110	0.034	0.895	0.809	0.992
Yes	0[a]		1		
Expectations towards authorities					
No	−0.141	0.012	0.868	0.777	0.970
Yes	0[a]		1		
Perceived ability to protect against heat stress					
No	−0.117	0.046	0.890	0.793	0.998
Yes	0[a]		1		

[a] refers to the reference categories.

Data availability

Data will be made available on reasonable request from the corresponding author.

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