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Research article

Where is the heat threat in a city? Different perspectives on people-oriented and remote sensing methods: The case of Prague

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ABSTRACT

Extreme heat in urban areas has a severe impact on urban populations worldwide. In light of the threats posed by climate change, it is clear that more holistic and people-oriented approaches to reducing heat stress in urban areas are needed. From this perspective we aim to identify and compare thermal hotspots and places with favourable thermal conditions, based on three different methods – thermal walk, participatory-based cognitive mapping, and remote sensing in a Central European city. Although major hotspots in large low-rise development zones were identified by all three methods, the overall agreement between on-site thermal sensation votes, cognitive maps and surface temperatures is low. In the urban canyon of compact mid-rise and open mid-rise development, the thermal walk method proved to be useful in the identification of the specific (parts of) streets and public spaces where citizens can expect thermal discomfort and experience heat stress, e.g. crossroads, arterial streets with a lack of greenery, north facing unshaded parts of streets, and streets with inappropriate tree spacing. Cognitive maps on an urban neighbourhood scale are not specific enough on a street level; however, as a supplementary method they can help identify discrepancies between on-site sensations and thermal conditions. For further research on effective and cost-efficient urban heat mitigation, we suggest combining thermal walks with numerical model simulations.

1. Introduction

Climate change is one of the most important environmental challenges that humanity currently faces and will continue to face in the coming decades. The increasing intensity, frequency, and duration of hot extremes has been one of the most certain aspects of climate change [1]. The worsening impact of hot extremes is expected to severely affect urban populations, whose percentage of the global population is continuously increasing [2]. Urban areas are also exposed to the additional heat load caused by modified radiation and energy balance [3].

Until recently, the study of urban thermal environments has mainly been from the climatological perspective traditionally associated with research into Urban Heat Island (UHI) [4,5]. In recent decades, considerable attention has also been paid to the possibility of using remote sensing-based methods, particularly satellite and aerial images, as means of gaining information about land surface

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temperatures (LST) [6–8]. The increasing availability of satellite images in the thermal radiation spectrum has led to an uncontrolled growth in the number of studies dealing with Surface Urban Heat Island (SUHI), surface hotspots, etc. This has resulted in the uncritical use of surface temperature-based analyses in the assessment of urban heat load and the vulnerability of urban areas to heat stress [9,10]. Yet the study of urban thermal environments and the management of urban heat load needs to be approached in a much more comprehensive way. In the context of the human-oriented paradigm in urban climate science, instead of geographically arbitrary spatial levels and (local) climate zones, humans inhabiting diverse urban environments are becoming the focus of research [11,12]. Accordingly, at the recent (2023) conferences: the 23rd International Congress of Biometeorology in Tempe, and the 11th International Conference on Urban Climate in Sydney, many contributors called for improvements in our understanding of outdoor thermal comfort as regards more adaptable and holistic approaches to heat stress mitigation in urban areas.

Human thermal comfort is defined as “the state of mind which expresses satisfaction with the thermal environment” [13]. A person feels thermally comfortable when feeling neither too cold nor too warm. In contrast, thermal discomfort may be accompanied by thermal strain and this results in the body suffering from thermal stress [14]. The key environmental component of thermal comfort is thermal exposure, which is determined by mean radiant temperature (MRT), air temperature, air humidity, and air velocity [15]. In urban climate and human biometeorology research, thermal exposure is characteristically incorporated into complex, widely recognized and available physiological “thermal comfort” indices, such as the Universal Thermal Climate Index – UTCI [16] and the (modified) Physiological Equivalent Temperature – PET/mPET [17–19].

When focusing on research into the psycho-physiological aspects of thermal comfort, researchers typically use surveys on Thermal Sensation Votes (TSV), Thermal Comfort Vote (TCV) [20,21], thermal expectation [22,23], and the thermal preferences of respondents at the moment [21,24]. Nevertheless, the results of studies conducted in diverse urban environments characteristically show substantial residual spatiotemporal variability in TSV, which cannot be explained by thermal conditions. Apart from thermal conditions, the unexplained spatiotemporal variability of TSV may be explained by various diverse factors such as: noise, air pollution, and odours [25], and a psychological effect (i.e. not primarily related to the effect of these factors on thermal exposure) caused by the openness, geometry, or design of an area [26,27]; the naturalness and character of greenery in an area [28,29]; the effects of frequent step changes in outdoor microclimate environments [30,31]; and mental (thermal) images of a place [32].

The mental thermal image of a place can be studied using the (geo)participation principle of employing the rapidly developing method known as cognitive maps. Cognitive maps, as understood by Gould and White [33], convey a sense of place, and are currently a popular and frequently used method in areas of citizen science [34]. Lenzholzer and Koh [35] compiled cognitive maps of people’s perceptions of microclimate, which were then compared with the results of (bio)climate measurements in three squares in the Netherlands. Klemm et al. [36] used cognitive maps to investigate which places in Utrecht (Netherlands) the residents considered to be

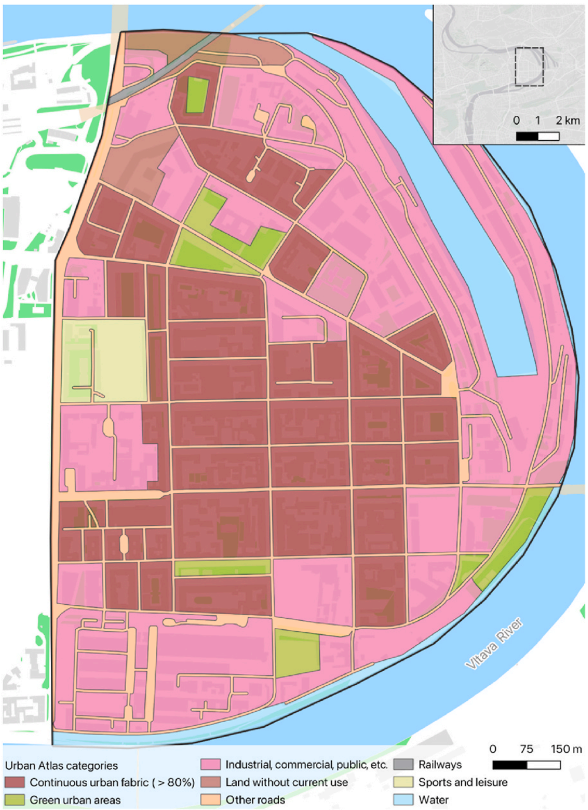

Fig. 1. Urban Atlas classes in the study area.

pleasant in terms of the thermal environment. Similarly, Aram et al. [37] used cognitive maps alongside TCV and asked people from a neighbourhood in Madrid's (Spain) city centre to mark the areas where they felt thermally comfortable. Throughout these studies, the mental thermal image of a place is assumed to be connected with (thermal) sensation, thermal comfort, and physical thermal environment, through complicated and not fully clarified relationships and mutual feedback. Based on the results from two Czech cities, Lehnert et al. [38] revealed mental thermal hotspots and coolspots, and they found that these mostly differed from LST based hotspots. Meanwhile LST remains the most frequently employed method for identifying hotspots in cities' strategic documents. Without a doubt, it is important to further investigate the reasons for mismatches between sensed, perceived, experienced, and real microclimatic conditions [39].

Our study goes beyond previous research and aims to identify locations with extremely hot thermal conditions (hotspots) during hot summer days, as well as locations that provide relatively less extreme thermal conditions (coolspots), using three different methods – thermal walk, participatory-based cognitive mapping, and remote sensing. The relevance of the results and the methods used will be further critically discussed from theoretical and application perspectives with respect to the overarching goal of this study: to disclose the potential of each method to contribute to our understanding of thermal (dis)comfort and heat stress in urban environments. This is of cardinal importance when considering efficient heat adaptation and mitigation measures in plans and actions.

2. Study area and methods

2.1. Study area

The study area was in part of the city of Prague, which is the capital and the largest city of Czechia, with a population of 1.357 million people and a total area of 496 km^2 [40]. The climate of Prague is classified as Köppen's Cfb (temperate oceanic climate). The average annual precipitation is 495 mm/year and the average annual air temperature is 9.0 °C, while the hottest month is July, with a mean of 18.9 °C and a mean maximum air temperature of 25.3 °C. The study period was August because it has the most stable weather. The mean air temperature during this month is 18.7 °C (based on a 30-year average from 1991 to 2020 and on meteorological station WMO ID 11518, Prague-Ruzyně) [41]. The city is located in the central part of Czechia, on a plateau divided by the Vltava River. For this study, a selected part of the Prague-Holešovice (Nové Holešovice) district was chosen. It is a quite closed district located in the left meander of the Vltava River (Figs. 1, 3–5). Although the river surrounds the entire area and could thus strongly influence the immediate vicinity, it is in a relatively deep canyon and is reinforced with stone and concrete. From the western part the selected area is enclosed by brownfields and a railway. The area is constructed in a rectangular street network and was built in the second half of the 19th century [42]. According to Local Climate Zones (LCZ), this area consists mostly of LCZ 2 (compact mid-rise buildings), LCZ 5 (open mid-rise buildings), LCZ 8 (large low-rise buildings), and LCZ G (water). Currently the former industrial face of this district is slowly being transformed into a modern administrative-residential district with cultural and social hinterlands.

2.2. Thermal walks

In this part of the study we performed a thermal walk campaign to evaluate subjective thermal sensations, using a Thermal Sensation Vote (TSV). Thermal walks allow pedestrians to analyse, identify and perceive thermal conditions in complex (urban) environments while walking [43–45]. In our campaign we used the ArcGIS Survey123 application where respondents self-reported real time TSV.

Our thermal walk campaign was held in the study area on August 3rd, 2022; it was the initial day of the first August 2022 heat wave episode, which occurred between August 3rd and 6th. According to the station Prague-Ruzyně (WMO ID 11518) the day was mostly cloudless. The maximum relative humidity occurred at night (85 %), dropping to 37 % during the day. The daily maximum air temperature was 30.6 °C, the mean daily air temperature was 23.3 °C and the mean daily wind speed was 1.6 m/s [46].

Ten people (five females and five males) in good physical condition and aged between 21 and 30 were chosen as a homogenous research group. Respondents subscribed to the necessary consent of use [47]. All participants engaged in a 3-h random walk through the study area with the instruction to try to visit several varied locations. The thermal walk was held from 1:15 p.m. to 4:15 p.m. local time to coincide with the most extreme thermal conditions; a period of 3 h was sufficient for participants to walk through the entire study area. During the walk everyone had to record TSV in the mobile application every minute on a nine-point scale [48] (Table A.1). Before starting the thermal walk the short-term thermal history was controlled with 1 h of acclimatisation in the shaded area of a park. Several conditions were set for the thermal walk: each respondent had to walk alone at a constant pace (about 4 km/h), everyone wore summer clothes (women wore their hair in a ponytail), and drank only soft drinks.

The data were further analysed in a QGIS environment. The locations of the given TSV were based on the devices' locations, which are not as precise as needed. In general, the use of GPS devices ('GPS devices' are considered to be all compatible devices that use any of the systems; GPS, GLONASS, Galileo, BeiDou, or QZSS) in urban environments has significant limitations. The precision of the coordinates is affected by high greenery and high buildings [49,50], and by the allowance and accuracy of the GPS chips in the devices. Some devices have a built-in chip that uses signals from other systems [51]. Proponents of current techniques (e.g. Ref. [52]) claim that modern dual-frequency smartphones can achieve submetre accuracy, and it is possible to mark a point directly on a map, but because the respondents were walking at a constant pace it was better to use GPS coordinates and then correct the position. For these corrections, precisely prepared routes were used. Data were post-processed using an algorithm for a minimisation of the distance between the measured and expected point locations. Each measured point was moved using its normal on-route position and its distance was compared with the previous point. If the distance was larger than 115 % of that expected, the point was moved closer, and when the distance was smaller than 85 % of that expected, the point was moved forward.

After the location correction, TSV were visualised (Fig. 3), and then all TSV scores were standardised via z-score. This process was done for each respondent separately, as their means and standard deviations differed.

2.3. Participatory mapping

Participatory mapping could be defined as a multiagent procedure that collects spatial data and allows citizens to communicate and express their knowledge, experience, and emotions concerning certain locations, for research aims and for decision-making using cartographic visualisation. It includes various methods such as cognitive mapping, sketch mapping, and participatory GIS [34,53,54].

Considering the climate and the reviewed previous experiences of people with this type of research, the participatory mapping campaign was held in the study area during the whole month of August 2022. The survey was carried out using a paper map questionnaire based on a questionnaire from pocitovemapy.cz. The target group of this research was local residents and regular visitors. Irregular visitors and tourists were excluded from the sample group as the research was designed to focus on the long-term experiences of respondents acquainted with the neighbourhood [35,55]; in our study we use the criteria: I live here (whole week) and/or I study/work here (at least 4 times a week). Respondents were asked to mark points and polygons on a map where they perceived thermal discomfort during hot summer days. For each marked location they could list the reasons the location is thermally uncomfortable and the kind of measures they suggest to make this location more thermally comfortable. Then participants could similarly mark points or polygons on locations where they felt thermally comfortable during hot summer days. Finally, personal questions, including gender, age, and residence (neighbourhood) were asked. The questionnaire was anonymous. A total of 181 valid answers were collected, including 853 geometries (147 points and 706 polygons) (Fig. A.1).

All obtained data were further analysed in QGIS, employing the create grid function, where a hexagonal grid was created, setting the parameters of horizontal/vertical spacing to 50m (horizontal spacing is the radius of the inscribed circle, each side of a hexagon is 18.5m). This size of hexagons proved to be adequate for the neighbourhood scale analysis [56]. For each hexagon, the “Reported Thermal Discomfort Score” (RTDS) (for thermally uncomfortable locations), and the “Reported Thermal Comfort Score” (RTCS) (for thermally comfortable locations) were calculated according to the Lehnert et al., 2021b [38] method.

2.4. Land surface temperature

To provide information about the physical thermal environment the data from two different satellite missions were used in this study; ECOSTRESS and LANDSAT (8 and 9). For this case study, 15 representative scenes from the summer of 2022 were selected, all without clouds over the study area and during the daytime. The scenes’ IDs and times are attached in Table A.2.

The ECOSTRESS module is located on the International Space Station (ISS) and has a spatial resolution of 69 × 38m. It has five spectral bands in the 8–12.5 μm range and an additional band at 1.6 μm for geolocation and cloud detection (six bands in total). The spectral range for Band 1 is 8.113–8.467 μm, Band 2 is 8.625–8.935 μm, Band 3 is 9.002–9.398 μm, Band 4 is 10.285–10.695 μm, and 11.7845–12.3955 μm is the range for Band 5. The L2 product that provides Land Surface Temperature and Emissivity (ECO2LSTE) was used [57].

Both LANDSAT satellites, 8 and 9, carry two instruments: an Operational Land Imager (OLI) sensor and a Thermal Infrared Sensor (TIRS and TIRS-2). The OLI sensor has nine bands (Bands 1–7 and 9 at 30-m resolution, panchromatic Band 8 at 15-m resolution), while TIRS has two bands (Bands 10 and 11, collected at 100-m resolution and re-sampled to 30 m). TIRS, as with TIRS-2, Band 10 spectral range is 10.60–11.19 μm and 11.50–12.51 μm for Band 11. LANDSAT 9’s TIRS-2 measures thermal radiance emitted from the land surface in two thermal infrared bands using the same technology that was used for TIRS on Landsat 8. However, TIRS-2 is an improved version of Landsat 8’s TIRS, with regard to instrument risk class and to the design aspect for minimising stray light. Landsat Collection 2, which includes scene-based global Level-2 surface reflectance and surface temperature science products, was used [58].

All scenes used in this study were resampled to 10 × 10m resolution using a cubic convolution method reprojected to EPSG 32633. For each of the scenes, a quantile rank of the temperature was calculated. The final composition represents the average quantile of the fifteen scenes calculated.

2.5. Comparisons and analyses of the results

Regarding the methodological differences and specifics of the three methods used in this study, the visual and descriptive comparisons relating to the experts’ knowledge in the study are important for the careful interpretation of the results. With regard to the quantitative analyses of the results, the hotspots based on the 90th, and 95th percentiles respectively, and the coolspots based on the 10th percentile of highest/lowest values are delineated. For the thermal walk, the percentiles are calculated for TSV points (Fig. 3), whereas for RTDS/RTCS and LST the percentiles are calculated for hexagons fully covering the study area (Figs. 4 and 5). Furthermore, the percent spatial overlaps of hotspots/coolspots based on different methods are calculated.

To compare the results for different types of urban structures and for their generalisation, we use the Urban Atlas surface classification, which is available for most European cities. As can be seen in Fig. 1, in our study area, with regard to the scope we can assess the thermal environment in three main classes: Continuous Urban fabric, Green urban areas and Industrial, commercial, public, military and private units (further “Mixed units”). For these classes, boxplots based on calculated percentiles were delineated (see Comparison of thermal conditions in dominant urban structures).

The research design of this study is summarised in Fig. 2.

3. Results

3.1. Real-time sensation hotspots and coolspots

From the analysis of thermal sensation during hot summer days in the Prague-Holešovice neighbourhood, it is evident that in the central part of the neighbourhood there is a higher concentration of relatively lower values of standardised TSVs; whereas in the peripheral parts there are largely relatively higher values of standardised TSVs (Fig. 3). This is obviously related to the openness of the space and higher solar radiation exposure.

More specifically, the highest values of standardised TSVs (thermal sensation hotspots) can be found in: the southern part of the harbourfront, which was built in the style of open landscape urbanism, and has mostly unshaded green spaces (1); an old marketplace area with a high proportion of impervious surfaces and lack of greenery (2); and a south-north oriented unshaded Argentine boulevard with heavy traffic (3). In those locations before standardisation, TSVs were predominantly very hot (+4) or hot (+3). The beginning of the peninsula and the adjacent street, Sanderova, with a Marina Island residential project (4) and the east-west oriented part of Jankovcova street (5) are also connected to high TSVs due to the lack of shade and greenery. Nevertheless, particularly in the case of east-west oriented streets, the differences in TSV between the southern parts of streets in the shade of buildings and the northern parts of streets exposed to direct solar radiation are well manifested (Ortenovo náměstí square 6, Dělnická street 7). It should be noted that even in east-west oriented streets trees can decrease TSVs in cases where respondents did not/could not for subjective/objective reasons choose their routes in the building-shaded part of a street (U Průhonu 8).

Focusing on the locations with the lowest standardised TSVs (thermal sensation coolspots), the results here confirm the importance of larger green zones for relief during hot summer days – most of the parks with shade and green elements can be considered as thermal sensation coolspots (6, Tusarův park 10), as can shaded and wider streets with tree-lined pavements separated from roads by parking spaces (8 and a northern part of Komunardů street 11). From the urbanistic perspective, it is also worth mentioning the relatively lower values of standardised TSV scores from the northern harbourfront ("Holešovice docks"), an area which was recently reconstructed following new urbanism principles (9). In all cases it must be taken into consideration that even in locations with relatively lower standardised TSVs, the TSVs before standardisation were mostly (+1) slightly warm or (+2) warm.

3.2. Mental hotspots and coolspots

Based on the neighbourhoods′ residents and regular visitors' experiences, the locations associated with thermally uncomfortable conditions ("mental hotspots") are arterial busy streets and especially the crossroads of these streets (Figs. 4–3, 7, 8, 11) (see Discussion). Further mental hotspots are related to open public areas with impervious surfaces and a lack of shade (1), and to large low-rise development areas with a lack of shade from mid-rise buildings such as marketplaces (2). Nevertheless, in Ortenovo náměstní Square (6), Komunardů (11) and its adjacent surroundings, the effect of thermal ambivalence is manifested, i.e. where the same location is considered by a substantial number of respondents as thermally uncomfortable and at the same time by some of the respondents as thermally comfortable (see Discussion section).

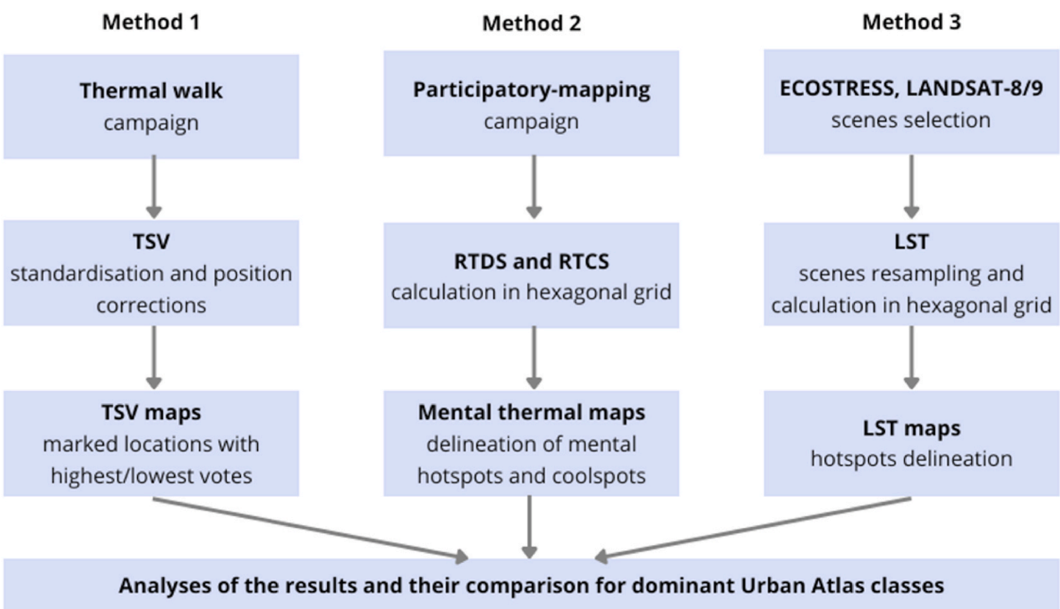

Fig. 2. The research design of the study (TSV – Thermal Sensation Vote, RTDS – Reported Thermal Discomfort Score, RTCS – Reported Thermal Comfort Score, LST – Land Surface Temperature).

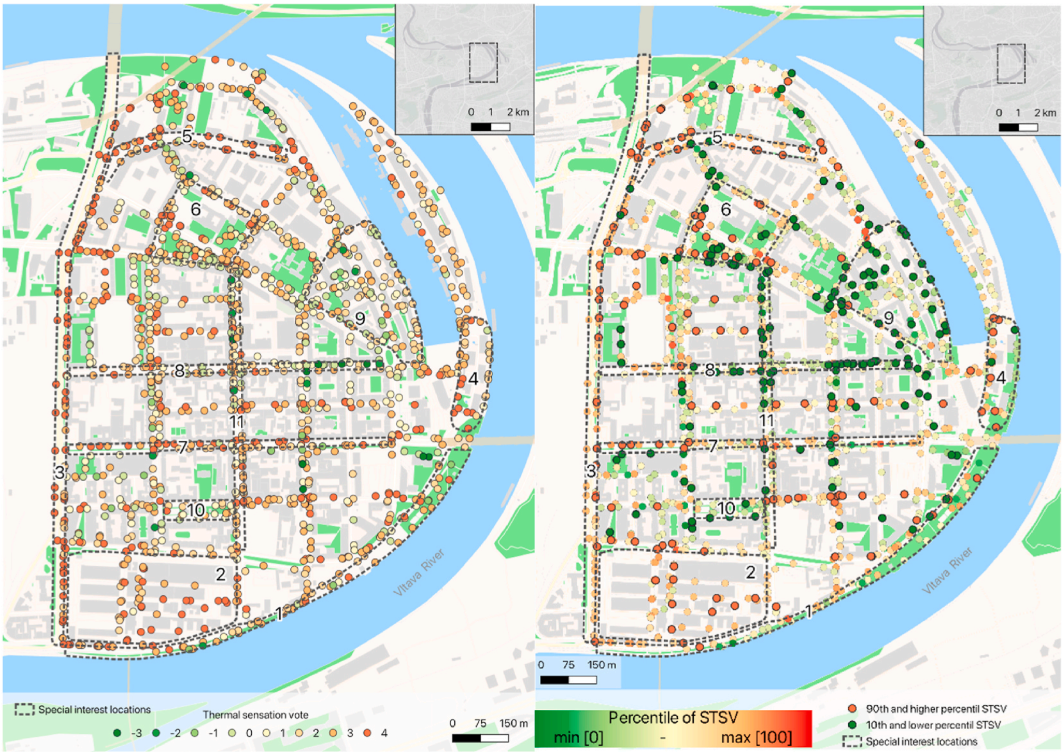

Fig. 3. LEFT: Thermal Sensation Votes before standardisation. RIGHT: Percentile of Standardised Thermal Sensation Votes (STSV) in the study area. Points of low STSV are coloured in green, and points of high STSV are coloured in red.

"Mental coolspots" (i.e. locations which a neighbourhood's residents and regular visitors have associated with thermally comfortable conditions) are particularly located in parks with high trees and water elements (6, 10). This result is in agreement with the findings of Lehnert et al. [38,59] and Aram et al. [37]. Nevertheless, in this study we revealed other types of coolspots that are mostly bounded by an adjacent large river. The first is the eastern part of the waterfront with a park (1), although there is a smaller proportion of high greenery and the lawn is divided by a network of paths (concrete, dirt), and the whole park is enclosed by a main road. The second extensive mental coolspot is Holešovice docks (9) – an area with revitalised buildings with green walls and roofs and plenty of other green features. This coolspot extends to the adjacent modern business park and its immediate surroundings and then in a line along the river, where there is sufficient shade from buildings and high greenery.

3.3. Surface temperature hotspots and coolspots

Finally, to provide information about the physical thermal environment in the neighbourhood, the relative spatial distribution of LST is analysed, and respective LST hotspots and coolspots are delineated (i.e. the areas with the highest and lowest surface temperatures respectively). The analyses of the relative distribution of surface temperatures in the study domain are based on fifteen representative scenes from three different sensors during the investigated summer period (Table A.2). The resulting land surface temperature map (Fig. 5 – left) averages forenoon and afternoon images from LANDSAT-8, LANDSAT-9 and ECOSTRESS satellites (this is suitable for comparison with the cognitive maps). Fig. A.3 shows another land surface temperature map calculated only from the afternoon scenes (ECOSTRESS), representing the period when the surface is at its hottest. Finally, Fig. 5 (right) represents LST during the thermal walk campaign using a scene from ECOSTRESS on August 3rd, 2022.

Based on the selected scenes, it is apparent that relatively higher LSTs are characteristic of the SW part of the neighbourhood. With respect to that, the surface temperature hotspot is located in the marketplace site (2) in the south, which has the characteristic of a large low-rise development (Fig. 5). Such a pattern is the result of the higher proportion of building surfaces not shaded by higher buildings and with less greenery in the SW part of the neighbourhood (Fig. A.3). However, as could be expected, surface temperature coolspots are, from a strictly statistical point of view, related to the water surface in the harbour in the area of the Vltava River (the Vltava River has a distinguishably low surface temperature but is outside the analysed area).

3.4. Comparison of thermal conditions in dominant urban structures

Focusing on the comparison of overlaps between hotspots and coolspots defined by particular methods, we find that 30 % of TSV hotspots (90th percentile of standardised TSVs) lie within mental thermal hotspots (90th and higher percentile of the RTDS), but only 8

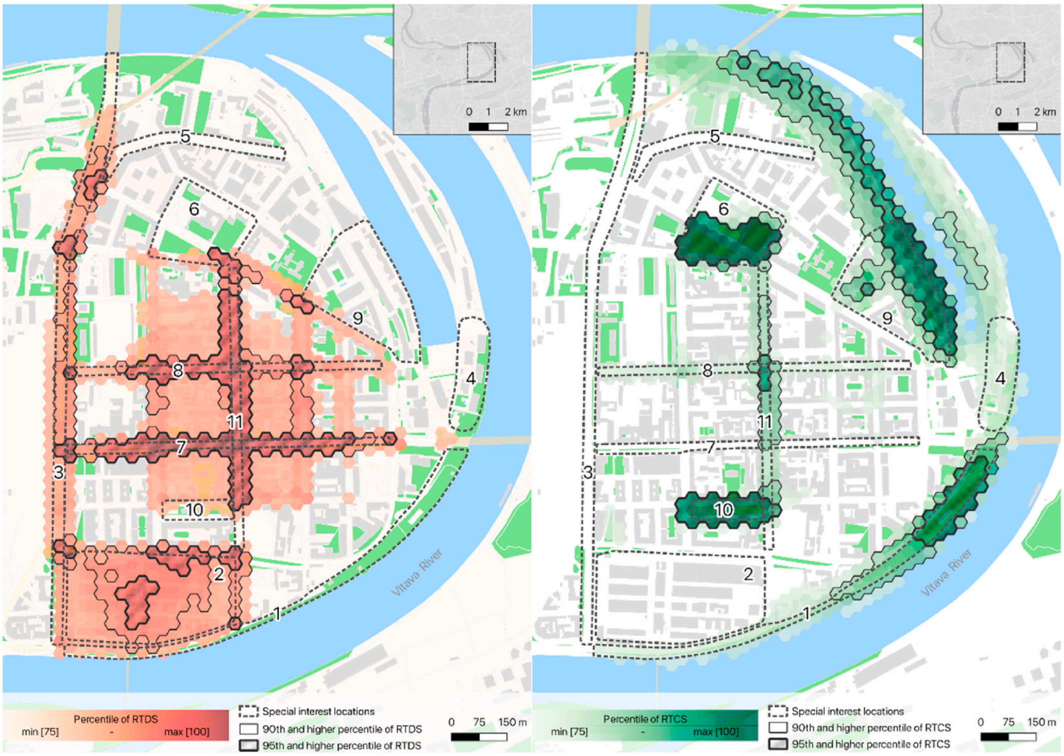

Fig. 4. LEFT: Mental hotspots defined by percentiles of Reported Thermal Discomfort Score (RTDS) identified by participatory mapping in the study area. RIGHT: Mental coolspots defined by percentiles of Reported Thermal Comfort Score (RTCS) identified by participatory mapping in the study area. Areas of the 75th and higher percentile are highlighted in red/green colour. The thin lines delineate hotspots/coolspots based on the 90th and higher percentile of RTDS/RTCS and the bold lines delineate hotspots/coolspots based on the 95th and higher percentile of RTDS/RTCS.

% of TSV hotspots lie within LST hotspots (based on the scene from the time of the thermal walk campaign, Fig. 5 – right). Mental thermal hotspots overlap with LST hotspots by 30 % of their total area.

In terms of coolspots, 39 % of TSV coolspots (10th percentile of standardised TSV) lie within mental thermal coolspots (90th and higher percentile of the RTCS). Only 4 % of TSV coolspots lie within the LST coolspots, which is due to the linkage to surrounding water bodies/rivers. Mental thermal coolspots overlap with LST coolspots by 18 % of their total area.

In terms of Urban Atlas land use/land cover classification in three predominant classes (see 2.5 Comparisons and analyses of the results) several (5) boxplots are depicted: TSV, RTDS-RTCS, LST (15 scenes/1 afternoon scene/8 afternoon scenes).

The Mixed units represent compact blocks of streets that provide shade during the thermal walk, and participants (as well as other pedestrians) could choose the shaded part of the street. Therefore the median of TSV is, for this category, even lower than for the category of Green urban areas. The significantly highest median of TSV was found for Mixed units (Fig. 6).

Completely different results for different Urban Atlas classes are obtained from the results of cognitive maps (RTDS-RTCS) based on the long-term experiences of respondents, who felt that the most thermally uncomfortable locations were in the Continuous Urban fabric Urban Atlas class (Fig. 7). However, the number of outliers and the thermal ambivalence of these locations must be pointed out (Fig. A.2). In contrast, Green urban areas were perceived as the most thermally comfortable (Fig. 7). Compared to the TSV-based results, this points to substantial differences between thermal expectation and actual thermal sensation (see Discussion).

The LST analysis shows the highest median of land surface temperatures for the Continuous Urban fabric Urban Atlas class (i.e. similar to the case of cognitive maps). Nevertheless, the satellite sensor largely senses roofs of buildings, and thermal anisotropy is also manifested (see Discussion). Comparing boxplots based on all selected satellite images (LANDSAT-8, LANDSAT-9, and ECOSTRESS), the class of Green urban areas has the lowest median (Fig. 8). Whereas when comparing boxplots based only on afternoon scenes (ECOSTRESS) (Figs. 9 and 10), lower median values are obtained for the Mixed units Urban Atlas class, where there is also a large interquartile range, due to its heterogeneity (includes both hotspot in the market and coolspot in the harbour, see Discussion).

4. Discussion and conclusions

4.1. Comparison of the results and implications

The results presented for the Prague-Holešovice neighbourhood indicate limited similarities in the spatial pattern of thermal hotspots and coolspots during hot summer days, as derived from three independent methods (thermal walks, cognitive thermal maps,

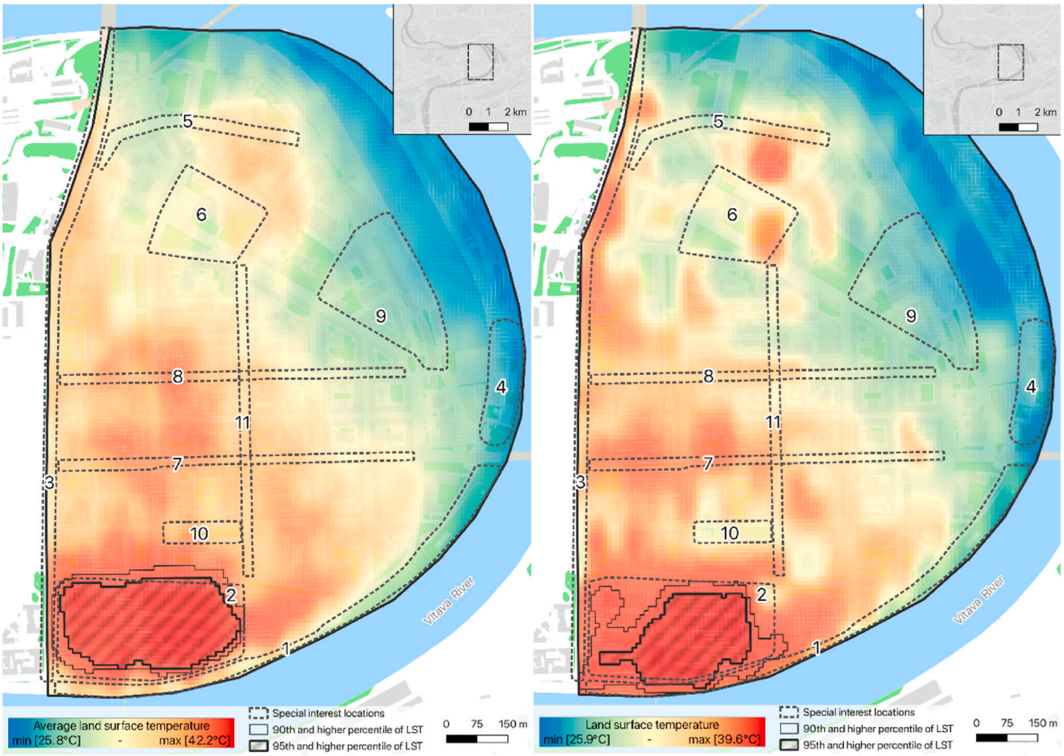

Fig. 5. LEFT: The average Land Surface Temperature (LST) derived from 15 representative scenes. RIGHT: LST derived from ECOSTRESS (August 3rd, 2022). Areas of low LST are coloured in blue, and areas of high LST are coloured in red. The thin lines delineate hotspots based on the 90th and higher percentile of LST, and the bold lines delineate hotspots based on the 95th and higher percentile of LST.

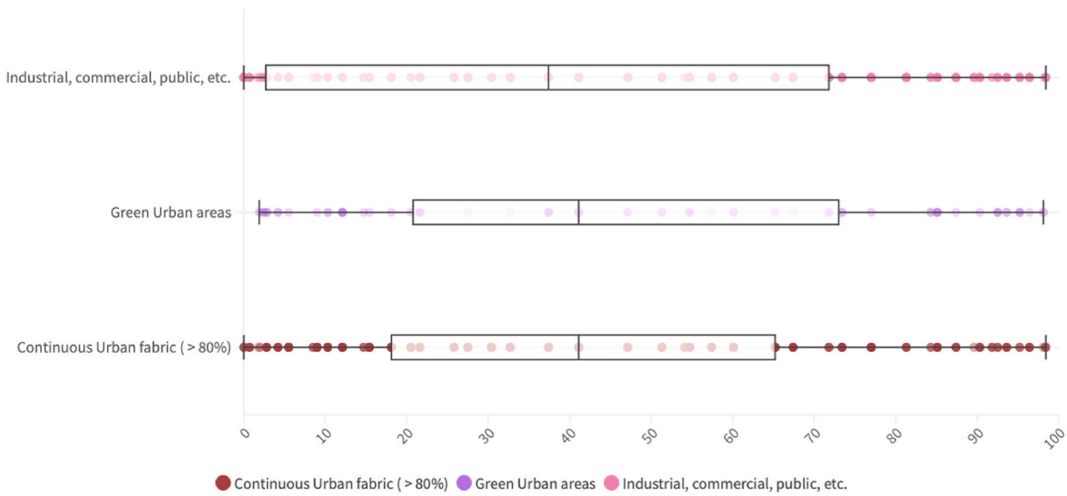

Fig. 6. Boxplot of the percentile of Thermal Sensation Vote (TSV) for dominant Urban Atlas classes in the study area.

and satellite imagery-based LST). Although some major hotspots and coolspots were identified across all three methods, the overall overlaps were rather low.

The TSV (Thermal Sensation Vote) corresponds better with satellite imagery-based LST (plan surface temperature) in large low-rise urban areas of Mixed units in the Urban Atlas class. Therefore, maps based on all three methods reveal a significant hotspot in the SW part in the Holešovice market and a noticeable coolspot on the NE part in the Holešovice docks. It is worth mentioning that based on the Geletič et al. [60] Prague local climate zone map, the Holešovice market is classified as LCZ 8 large low-rise and the Holešovice docks area between LCZ 8 and LCZ 5 open mid-rise (after recent revitalisation it more closely resembles LCZ 5). New mostly mid-rise development is well integrated with the original water area and contains a larger fraction of high greenery. This obviously leads to a

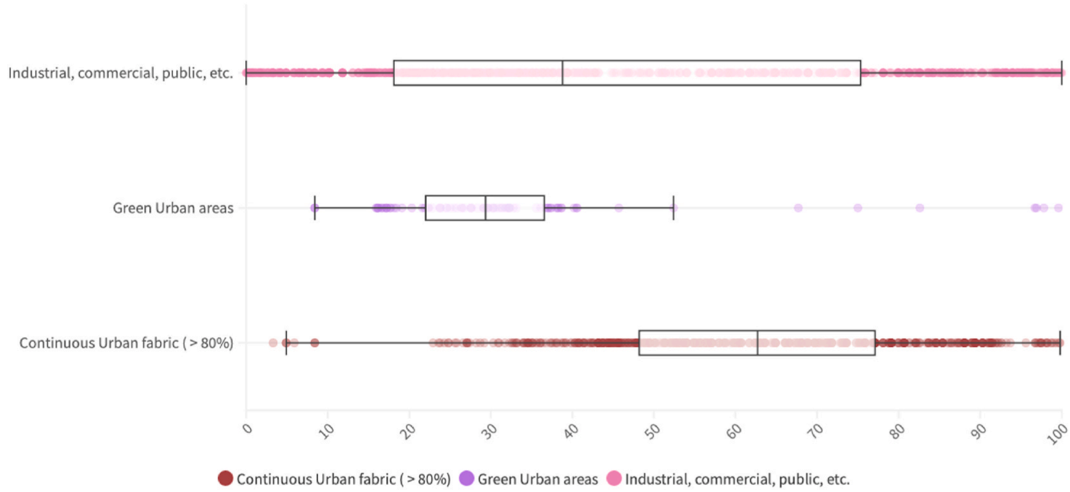

Fig. 7. Boxplot of the percentile of the difference of Reported Thermal Discomfort Score (RTDS) and Reported Thermal Comfort Score (RTCS) for dominant Urban Atlas classes in the study area.

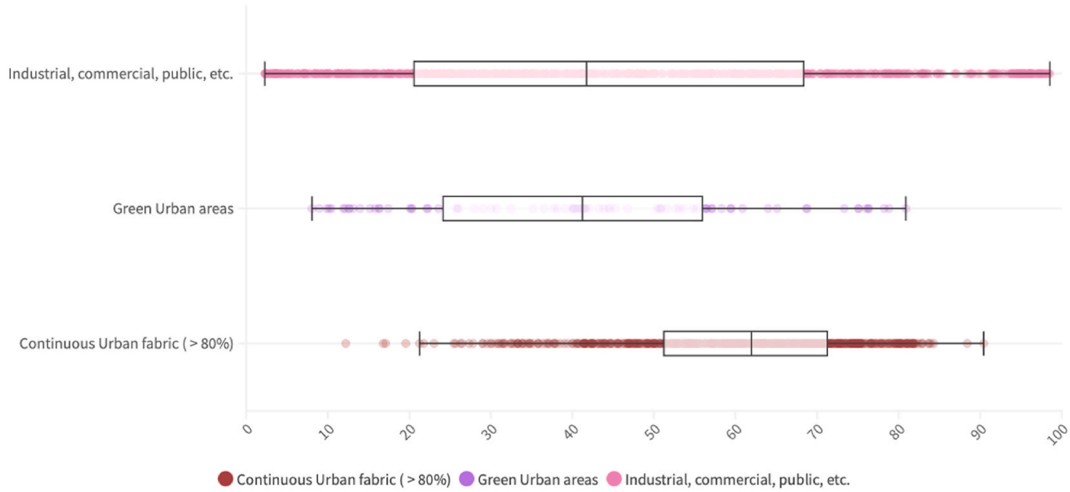

Fig. 8. Boxplot of the percentile of Land Surface Temperature (LST) derived from 15 representative scenes (LANDSAT-9, LANDSAT-8, ECOSTRESS) for dominant Urban Atlas classes in the study area.

positive effect on thermal sensation, on the mental thermal image of the place and on land surface temperature. This revitalisation therefore seems to be an example of good practice for overheated LCZ 8/10 specifically located in central parts of Central European cities [61].

Furthermore, TSV's spatial pattern and cognitive maps also confirm the importance of even several hundred square metres or a few hectares of high greenery zones (parks) for relief during hot summer days, and this therefore supports the importance of green zones in the improvement of thermal conditions, thermal comfort, and reduction of heat stress in urban areas [62,63]. Alternatively, LST and cognitive maps mostly fail to capture open spaces with low greenery or even water, where high TSV can occur. This is reflected in the overall evaluation of thermal environments in the Green urban areas Urban Atlas class, where respondents using cognitive maps evaluated this category compared to the rest of the study area relatively better than actual TSV. Such discrepancies between the mental thermal image of a place and its thermal sensation occur specifically in green spaces with low vegetation and no shading, since differences between thermal expectations and real thermal conditions can contribute to heat stress [20]. At the same time, more research on open green spaces with low vegetation is needed, since specific differences in thermal sensation (and thermal comfort) between "sun seekers" who tend to concentrate in sunlit green areas, looking for environmental stimuli, and passers-by can be expected [38].

Inside the streets of the Continuous Urban fabric Urban Atlas class (in the study area of mostly LCZ 2 compact mid-rise and LCZ 5 open mid-rise) cognitive maps drawn on a neighbourhood scale were found to be not very helpful in the study of thermal conditions. Similarly, satellite-derived LST were confirmed to be inappropriate for research on thermal conditions in such urban structures (see section 4.2 Study limitation). Alternatively, the thermal walk campaign seems to provide very detailed and useful results where TSV

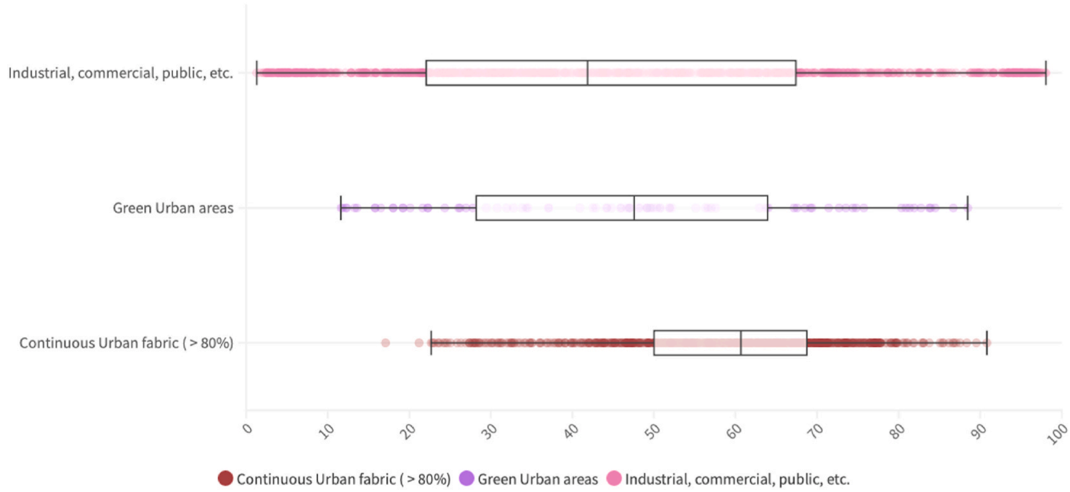

Fig. 9. Boxplot of the percentile of Land Surface Temperature (LST) derived from 8 representative afternoon scenes (ECOSTRESS) for dominant Urban Atlas classes in the study area.

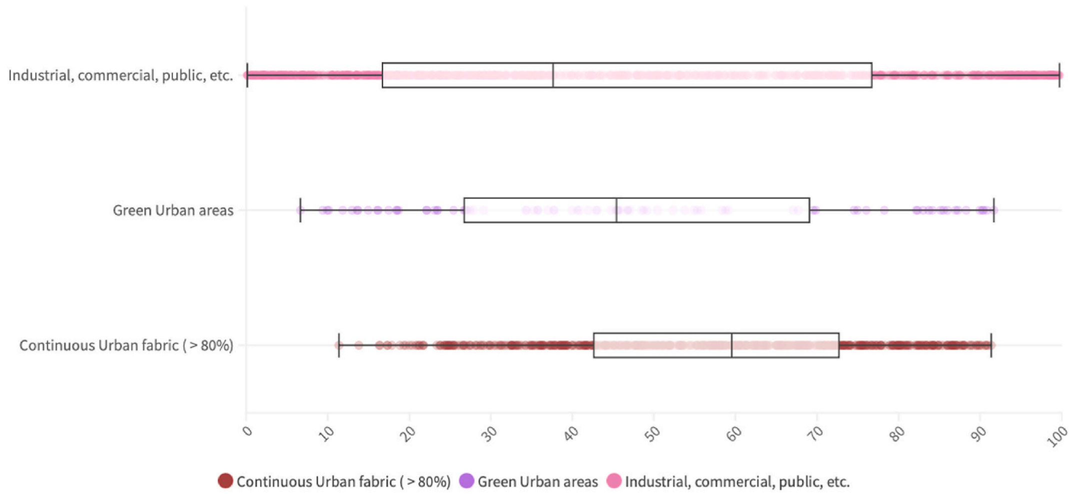

Fig. 10. Boxplot of the percentile of Land Surface Temperature (LST) derived from ECOSTRESS (August 3rd, 2022) for dominant Urban Atlas classes in the study area.

hotspots are located in busy and arterial streets with a lack of greenery, and on the northern unshaded parts of these streets, especially on crossroads.

Crossroads and streets with rush hour traffic also add noise and traffic-related emissions to the higher values of TSV and overall (thermal) discomfort in the identified TSV hotspots [25]. These locations need particular attention from local governments. Concurrently, relatively lower TSVs located in shaded and wider streets with a pavement separated from the road by parking spaces (Fig. 3, location 8) correspond with recent simulations by Geletič et al. [12] on thermal exposure variations in another densely populated Prague neighbourhood and emphasise the importance of the appropriate location of trees [64].

4.2. Study limitations and further research

Primarily, it is worth clearly disclosing that on the theoretical-methodological level, we are working with methods that have a rather different ontological basis and one has to be very careful employing any quantitative comparisons. Limitations and further prospects for particular methods are discussed below.

With regard to the thermal walk campaign, from the perspective of technical support our method allows for the mentally unbiased localization of a place. However, the use of regular smartphones with conventional GPS sensors creates inaccuracies in street canyons, and it was a complicated process to remove these inaccuracies. Therefore, for a very accurate survey, it is possible to equip respondents with more accurate geodetic GPS devices. Alternatively, the development of the algorithm for GPS correction is the right way to extend this method to the human population and thereby provide the method of thermal walks as a participatory measurement and mapping exercise in the (near) future. This could be an important step in improving the representativeness of the subjective data obtained, which must be always taken into consideration in thermal walk campaigns that focus on groups of respondents.

In the present study, despite the large number of points/scores and their standardisation, it is based on a focus group of a small number of respondents. Therefore, for gaining further insights it is undoubtedly advisable to repeat the research with other groups of different ages, health conditions, etc. It should also be emphasised that our thermal walk campaign was focused only on afternoons, when temperatures are at their highest. However, recent studies prove that the effects on TSV of various urban structures, and particularly blue and green features, vary over time during a day [26,29,65]. Moreover, studying the psychological component of thermal comfort more deeply, it is possible to add more evaluated indicators simultaneously (e.g. TCV) [66]. However, more observed indicators might cause the respondent to be too busy with the research itself, resulting in research conditions that are far from the normal [67,68]. Regarding this we believe that by developing an application that records respondents voices this situation could be resolved.

Concerning the cognitive thermal map, we consider the sample to be representative and relatively balanced at the neighbourhood level. However, with respect to Klemm et al. [36] and Brown and Kyttä [69], it should be taken into account that about ¾ of possible respondents do not have preferences for specific thermal comfort zones, and the result is therefore partly biased by those who have some preferences and are consequently more willing to complete the questionnaire (map). The problem with the representativeness of the resulting collective cognitive map is that locations that are easily accessible from all parts of the study area are more often identified by respondents, as opposed to the relatively inaccessible locations in peripheral parts [70]. The latter locations (e.g. Komunardů street (11) (Fig. A.2) could therefore be more frequently considered (falsely) to be thermally ambivalent [59,71]. Based on a comparison of cognitive map-based thermally ambivalent locations with the spatial distribution of both standardised and non-standardised TSVs, it is obvious that people may have different experiences with a location depending which side of the street they normally walk on, where they are coming from (e.g. home, bus, shop), and at what time they walk there (whether the street is sunlit or shaded at that time), and thus what are their thermal expectations and preferences at that moment. This is evident, in such cases as the Urban fabric Urban Atlas class where entire streets are marked as thermally uncomfortable, yet TSV on these streets indicates the possibility of passage (e.g. shaded part of the street). Cognitive maps therefore could not be used to distinguish differences in Continuous Urban fabric Urban Atlas class (in the study area corresponding to LCZ 2 compact mid-rise and LCZ 5 open mid-rise according to Geletič et al., [60]) within a street. Here, it is worth mentioning that higher detail on the mental thermal image of a place could be obtained if participatory mapping was focused on a specific street, square, or park [35,37].

Third, as regards surface temperatures, despite improving algorithms/models for brightness temperature correction, unknown spatial variability of surface emissivity is the first significant problem for determining true (kinetic) surface temperature in heterogeneous 3D urban developments [72]. Another problem which is not easy to overcome for remote sensors with directional or limited fields of view is thermal anisotropy [73] that implies sensitivity to micro-scale surface temperature variation due to differences in the effective 3D radiometric source area with a viewing angle which is more a product of an urban form combined with a surface temperature variation, than a property of the individual surface materials [72]. An inherent problem that should be highlighted is the proportion of shaded 3D structures in urban environments, which varies with respect to the viewing angle of the sensor, the position and height of the Sun and the particular 3D structure of a development. In midrise Continuous Urban fabric Urban Atlas class a significant difference can be expected between horizontal surfaces viewed from above (plan surface temperature) and pedestrian surface temperature (temperature of surfaces emitting radiation toward ground-level pedestrians (roads, building walls, undersides of trees) [74]. It is evident that only the last mentioned example reflects a human/people oriented approach to urban climate research [12]. Therefore, it is important to emphasise that even if thermal anisotropy were 'normalised' or corrected (e.g. to a nadir viewing value), satellite imagery-based LST still would not represent the pedestrian surface temperature in a street canyon.

A number of numerical models can be used to simulate pedestrian level surface temperatures, supported by validation measurements of surface temperatures in or above a street [74–76]. Therefore in further studies, despite dozens of other difficulties and uncertainties related to numerical modelling, it seems to be more promising to use validated fine-scale resolution numerical models which can provide more complex information about the thermal environment than just surface temperature; i.e. calculation of human thermal exposure and related meteorological indices.

5. Conclusion

In our study we experimentally used the three methodologically different approaches of: thermal walk, cognitive maps and satellite imagery-based LST to identify hotspots and coolspots during hot summer days in the Prague-Holešovice neighbourhood. There are substantial differences in the outputs of all three methods and only a few key hotspots and coolspots were simultaneously identified by all three methods. In terms of the agreement of all three methods the results: i) provide strong evidence that overheated large low-rise developments located in busy central parts of cities need the attention of urbanists and local policymakers ii) show the importance of blue-green infrastructure for the mitigation of urban heat load, for the reduction of human heat stress, and for adaptation to climate change in urban areas. At the same time, the described differences among the methods used are important caveats for researchers and municipalities who tend to uncritically identify overheated locations or locations with higher heat threat using simple and single methods.

In the urban canyon of compact mid-rise and open mid-rise development, the thermal walk method proved to be useful in the identification of the specific (parts of) streets and public spaces where citizens can expect thermal discomfort and experience heat stress, such as crossroads, arterial streets with a lack of greenery, northern unshaded parts of streets, and streets with inappropriate tree spacing. We believe that such detailed information is needed for effective and cost-efficient urban heat load mitigation and climate change adaptation measures in urban areas. Alternatively, cognitive maps on an urban neighbourhood scale are not specific enough on a street level. They should be used solely as a supplementary method, e.g. to explore the differences between thermal expectations and thermal sensation and real thermal conditions. Satellite measured plan surface temperature has very limited potential to contribute to the current human-oriented urban climate research, as it cannot capture the variability of thermal conditions on a street level (urban canyons) of the Continuous Urban fabric Urban Atlas class (in our case study represented by LCZ 2 and LCZ 5). Therefore, for further research we suggest more thermal walk campaigns at different times of the day, and their fine-scale comparison with measured and particularly modelled thermal exposure would be particularly useful for further developments in human-oriented research and approaches to urban climate management.

Ethics statement

This study was approved as a part of contract research (PRF/2022/0187 - SD. No. D001/2022) by decision bodies of both institutions (Palacký University Olomouc & Czech Academy of Sciences) and was approved by Statement of compliance with ethical standards of research involving humans as subjects Ref. No.: EK-KGG-UP-004, dated June 8, 2022. All participants provided informed consent to participate in the study and provided written informed consent for the publication of their anonymised case details.

Data availability statement

The data that support the findings of this study are openly available at [https://zenodo.org/records/11635158].

CRediT authorship contribution statement

Veronika Květoňová: Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Jiří Pánek:** Visualization, Software, Formal analysis, Data curation. **Jan Geletič:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Petr Šimáček:** Writing – review & editing, Visualization, Software. **Michal Lehnert:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e36101.

Appendices.

Table A.1
Nine-point thermal sensation scale (ISO 10551, 2019).

Scale	Thermal sensation
4	Very hot
3	Hot
2	Warm
1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold
−4	Very cold

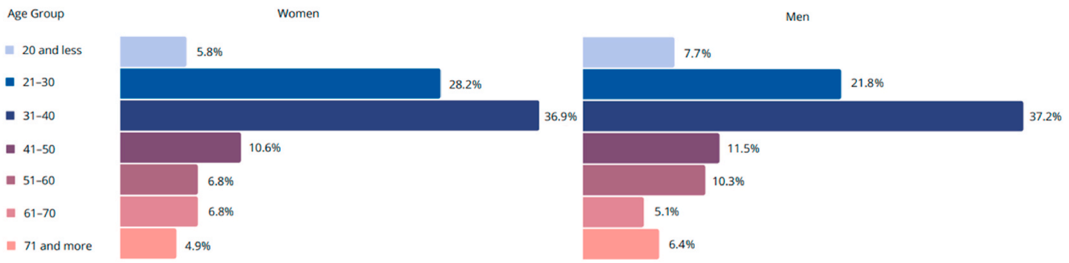

Fig. A.1. Demographic structure of respondents involved in the participatory-based mapping campaign.

Table A.2
Detailed information about satellite scenes used in this study.

Satellite	Date	Time	Scene ID
LANDSAT-9	*03.07.2022*	*09:57:18*	LC09_L2SP_192025_20220703_20230408_02_T1
LANDSAT-9	*19.07.2022*	*09:57:19*	LC09_L2SP_192025_20220719_20230406_02_T1
LANDSAT-8	*20.07.2022*	*09:51:32*	LC08_L2SP_191025_20220720_20220726_02_T1
ECOSTRESS	*27.07.2022*	*16:32:47*	ECO2LSTE_001_SDS_LST_doy2022208163247
LANDSAT-9	*28.07.2022*	*09:51:16*	LC09_L2SP_191025_20220728_20230406_02_T1
ECOSTRESS	*02.08.2022*	*16:31:52*	ECO2LSTE_001_SDS_LST_doy2022214163152
ECOSTRESS	*03.08.2022*	*15:43:15*	ECO2LSTE_001_SDS_LST_doy2022215154315
LANDSAT-9	*04.08.2022*	*09:57:32*	LC09_L2SP_192025_20220804_20230404_02_T1
ECOSTRESS	*04.08.2022*	*13:17:52*	ECO2LSTE_001_SDS_LST_doy2022216131752
ECOSTRESS	*04.08.2022*	*14:54:01*	ECO2LSTE_001_SDS_LST_doy2022216145401
LANDSAT-8	*05.08.2022*	*09:51:43*	LC08_L2SP_191025_20220805_20220818_02_T1
ECOSTRESS	*07.08.2022*	*14:05:32*	ECO2LSTE_001_SDS_LST_doy2022219140532
ECOSTRESS	*08.08.2022*	*14:53:44*	ECO2LSTE_001_SDS_LST_doy2022220145344
ECOSTRESS	*15.08.2022*	*10:50:29*	ECO2LSTE_001_SDS_LST_doy2022227105029
LANDSAT-9	*29.08.2022*	*09:51:29*	LC09_L2SP_191025_20220829_20230331_02_T1

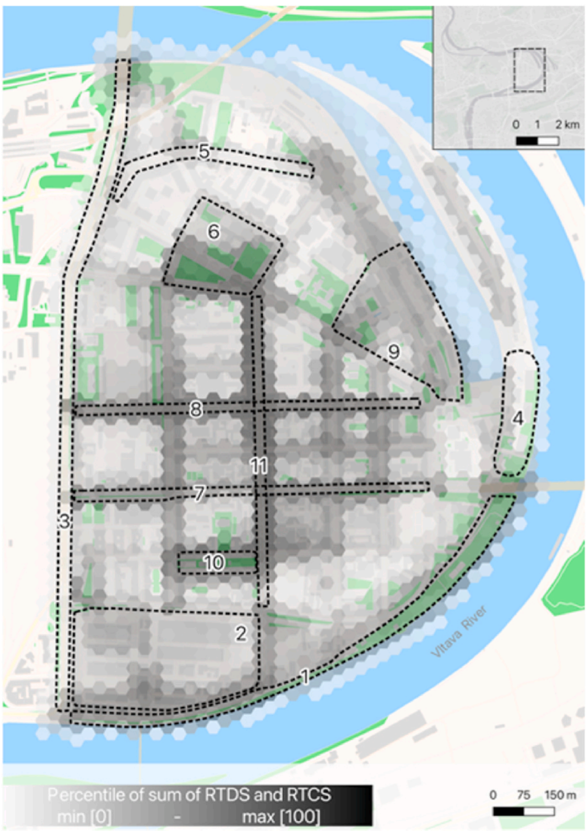

Fig. A.2. Percentile of the sum of Reported Thermal Discomfort Score (RTDS) and Reported Thermal Comfort Score (RTCS) identified by participatory-based mapping campaign in the study area. Areas of low percentile are highlighted in light grey and areas of high percentile are highlighted in dark grey colour.

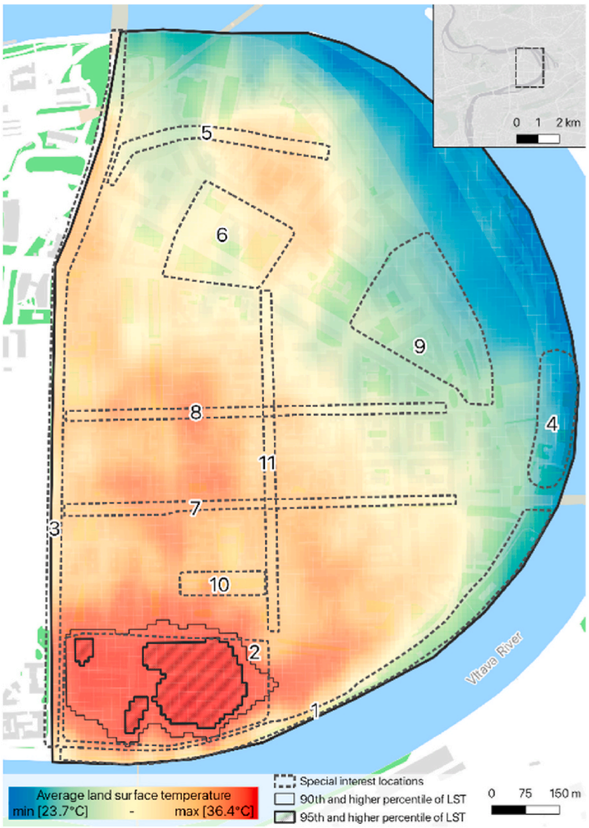

Fig. A.3. The average Land Surface Temperature (LST) derived from 8 representative afternoon scenes (ECOSTRESS) in the study area. Areas of low LST are coloured in blue, and areas of high LST are coloured in red. The thin line delineates hotspots based on the 90th and higher percentile of LST, and the bold lines delineate hotspots based on the 95th and higher percentile of LST.

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