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# Using Google Street View photographs to assess long-term outdoor thermal perception and thermal comfort in the urban environment during heatwaves

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The outdoor thermal comfort of urban residents is negatively affected by heatwaves that are becoming more frequent and severe with the ongoing climate crisis. As such, the assessment of outdoor perception and comfort during heatwaves has become an important ingredient of successful urban adaptation strategies. However, systematic assessment of long-term thermal perception across a large number of places and large populations of people is difficult. In this study, we consider an approach to the assessment of long-term thermal perception that combines features of currently used approaches (i.e., use of rating scales of thermal perception, use of surveys, and the use of photographs representing places) and we provide some preliminary validation of this approach. Specifically, across three studies conducted in two Czech cities, we show that long-term thermal perceptions for a large sample of 1,856 urban places can be elicited in a large sample of city residents (total  $N = 1,812$ ) using rating scales in off-site surveys complemented with visual representations of the target locations. In Studies 1 and 2, we partially validate this approach by showing that such long-term thermal perceptions can be traced back to average surface temperature, sky-view factor, and the presence of blue and green infrastructure, all factors that the literature relates to thermal perception. Moreover, we show evidence that observers can reliably glean these properties from the visual representation of places. In Study 3, we provide additional evidence of the predictive validity of such long-term thermal perceptions by showing that they predict place-related activities (waiting and walking) and the place preference of other people more than one year later. Thus, this approach to the measurement of long-term thermal perception related to heatwaves can be a useful addition to currently used approaches.

## KEYWORDS

long-term thermal perception, expected thermal comfort, heatwave, climate adaptation, urban planning–social aspects, urban greenery, remote sensing

## 1 Introduction

The climate crisis will increase the frequency and severity of heatwave impacts in urban areas resulting in many detrimental effects on residents, including negative impacts on their thermal comfort (Shukla et al., 2019; Aram et al., 2020). For urban adaptations to be effective and efficient, adaptation measures should prioritize those urban areas where the impacts on residents' thermal comfort are potentially the largest (Aram et al., 2020).

One of the aspects of outdoor thermal comfort that is particularly relevant for policymakers is the long-term (subjective) thermal perception (Lenzholzer, 2010). Long-term thermal perception is essentially a thermal expectation that people associate with a certain place they know but also places that have not yet visited. Long-term thermal perceptions are based on people's experience with the environment and with similar environments (Nikolopoulou et al., 2001; Lenzholzer, 2010; Eysenck and Brysbaert, 2018). Such long-term thermal expectations are important because they influence how people adapt to thermal conditions by, for instance, adjusting their clothing style or changing their commuting patterns (Langevin et al., 2015; Sun et al., 2018).

In this study, we present an approach to the assessment of long-term thermal perception that combines features of currently used approaches (i.e., use of rating scales of thermal perception, use of surveys, and the use of photographs representing places) and we provide some preliminary validation of this approach. We believe that this approach might be useful for theoretical as well as practical purposes as it offers some methodological benefits, namely that it can cover large representative samples of spatial points and participants and thus allow for valid generalizations.

## 2 Outdoor thermal perceptions

Early research in thermal perception focused almost exclusively on the physiological aspects of thermal perception. Researchers have developed complex indices to characterize indoor perception such as the *Standard Effective Temperature* and *Predicted Mean Vote* (Fanger, 1970) to characterize expected thermal comfort based on micro-climatic characteristics such as air temperature, air movement, relative humidity, radiant temperature, and a host of personal characteristics such as clothing and metabolic level. Similarly, complex indices, such as the *Physiological Equivalent Temperature* (Mayer and Höppe, 1987) and *Outdoor Standard Effective Temperature* (Pickup and de Dear, 2000) were later developed to characterize the physiological aspects of outdoor thermal perception based on micro-climatic and personal variables.

Although the physiological aspects of thermal perception are important, some literature points to the limitations of

physiological models of thermal perception (Auliciems, 1981) and the importance of psychological aspects of thermal perception and thermal comfort (Nikolopoulou et al., 2001; Thorsson et al., 2004). The literature also shows that subjective thermal perception is important because it is predictive of the use of public spaces (Eliasson et al., 2007; Walton et al., 2007) and outdoor activities (Thorsson et al., 2007).

### 2.1 Long-term thermal perception

Especially of interest to policymakers is long-term thermal perception, sometimes referred to as thermal expectation (Lenzholzer, 2010). Long-term thermal perception is based on people's experience with the environment and with similar environments (Nikolopoulou et al., 2001; Lenzholzer, 2010; Eysenck and Brysbaert, 2018). People plan their outdoor activities based on their thermal expectations; long-term thermal expectations also influence how people adapt to thermal conditions by, for instance, adjusting their clothing style or changing their commuting patterns (Langevin et al., 2015; Sun et al., 2018). The long-term thermal perception of places is based on repetitive experiences with these and similar places; these repeated experiences become ingrained in people's memory (Klemm et al., 2015a).

Some scholars have suggested that people use visual cues available in the environment to infer their thermal perception of that environment (Lenzholzer and van der Wulp, 2010). Such attribution is probably driven by a well-known psychological mechanism whereby people use distal cues to infer probabilistically properties of objects that they cannot directly observe (Brunswick, 1956). For instance, squares that are very wide, open, or decorated with materials considered "cold" (e.g., stone and concrete) are perceived as uncomfortable (Lenzholzer and van der Wulp, 2010). On the other hand, the presence of green infrastructure improves perceived thermal comfort (Klemm et al., 2015b), as we will discuss in some detail later.

## 3 Approaches to assessment of outdoor thermal perception

### 3.1 Subjective thermal perception votes

One of the approaches to thermal perception assessment is based on the use of subjective thermal perception scales. For instance, Ahmed (2003) conducted a survey in six locations in the city of Dhaka, Bangladesh, which represented six local climate zones (e.g., street canyons). He then related the personal thermal sensation votes of interviewees with the micro-climatic characteristics of the climate zones to identify which zones

were perceived as more ambient and under what conditions. Another study by [Katzschner \(2004\)](#) explored momentary thermal perception in two squares in the city of Kassel, Germany using a five-point Likert scale of thermal perception. The study resulted in maps of perceived thermal comfort of selected localities but did not result in a comparison of subjective thermal perception and objective thermal data. However, the correspondence between the micro-climatic conditions (sky clearness index, wind speed, and air temperature) and subjective thermal perception in four places (square, courtyard, park, waterfront) in the city of Gothenburg, Sweden, was clearly found in a study by [Eliasson et al. \(2007\)](#). A more dynamic and continuous picture of thermal perception can be obtained with the relatively new method of thermal walks whereby micro-climatic data together with subjective data from participant questionnaires can be gathered over the course of a pedestrian route ([Vasilikou and Nikolopoulou, 2020](#)). One of the limitations of existing studies using subjective thermal perception scales is that these typically evaluate perceptions related to a very limited number of specific places or spatial points.

### 3.2 Cognitive maps

As an alternative approach to thermal perception assessment, some researchers have used cognitive thermal perception maps (e.g., [Lenzholzer, 2010](#); [Lenzholzer and Koh, 2010](#); [Lehnert et al., 2021](#)) that can potentially cover large areas. In cognitive mapping, participants are typically asked to indicate, using maps, spatial areas where they think they would have certain thermal perceptions (such as feeling too cold or too hot). Such information can be then aggregated across all participants, resulting in a map that displays where most people would have certain thermal perceptions. Such cognitive mapping can be done for selected urban areas ([Lenzholzer, 2010](#); e.g., [Lenzholzer and Koh, 2010](#)) or it can span a whole city ([Lehnert et al., 2021](#)).

Even though cognitive maps generally match other thermal perception data, they have been often found to overrepresent extreme thermal perceptions ([Lenzholzer and Koh, 2010](#); [Lehnert et al., 2021](#)). In other words, participants tend to better recollect areas where they experienced extreme thermal perceptions, such as feeling too windy, too cold, or too hot. This is in line with psychological theorizing that highly negative phenomena (e.g., experiencing an extremely uncomfortable environment) affect human perception more than relatively positive phenomena (e.g., experiencing only a mildly uncomfortable environment; [Rozin and Royzman, 2001](#)). Another limitation of studies using cognitive maps (but also most studies using subjective rating scales) is that they are conducted on convenience samples of participants that do not represent any known population.

### 3.3 Photograph-assisted thermal perception assessment

Yet another but rather rare approach to the assessment of long-term thermal perceptions is based on the use of photographs to assist thermal perception measurement. Photographs can be used as stimuli in landscape analyses, particularly in studies of people's preferences related to certain features of the landscape ([Rodiek and Fried, 2005](#)). Visual representation of places was also used by economists in choice experiments to represent any visually accessible attributes of places before people make decisions related to these places ([Patterson et al., 2017](#)). Some scholars have suggested that visual appraisal of photographs could help to get a better understanding of how observable features of the environment affect people's perception of the microclimate ([Lenzholzer and Koh, 2010](#)). As such, photographs could potentially convey visual information upon which people base their long-term thermal perception.

Despite their potential usefulness in assisting the measurement of long-term thermal perception, photographs of places have been rarely used in the assessment of thermal perception in specific places. As far as we are aware, only the study by [Cortês et al. \(2020\)](#) used photographs to assist thermal perception assessment. These authors used photographs of three different places in Porto, Portugal, and asked their participants to select the most comfortable and most uncomfortable environments among them. They found that these choices matched data from *in situ* measurements of thermal perceptions and suggested that the decision tasks using visual representations of places can complement conventional *in situ* assessment of thermal perception.

## 4 Effect of blue and green infrastructure on thermal perception

Perceived thermal comfort is linked to psychological, physical, psychological factors, and behavioral factors ([Chen and Ng, 2012](#)). Among these, naturalness and aesthetics of the place, and experience with the place play an important role as factors of perceived outdoor thermal comfort ([Nikolopoulou and Steemers, 2003](#); [Eliasson et al., 2007](#); [Nikolopoulou, 2011](#)).

Given these patterns of perceived thermal comfort, it is not surprising that the presence of green infrastructure improves thermal comfort in outdoor places ([Höppe, 2002](#); [Nikolopoulou and Steemers, 2003](#); [Knez and Thorsson, 2006](#); [Lin, 2009](#); [Lenzholzer and van der Wulp, 2010](#); [Klemm et al., 2015a, 2015a](#); [Aram et al., 2019, 2020](#)). There is also some evidence that the presence of blue (i.e., water) infrastructure improves thermal comfort in outdoor places, particularly in places that are exposed to high temperatures ([Völker and Kistemann, 2011](#); [Gao et al., 2018](#)). This is, again, not surprising given that the

presence of water infrastructure reduces heat load in outdoor spaces (Broadbent et al., 2018).

## 5 Current study

In this study, we propose an approach to long-term thermal perception assessment that combines previously used methods, namely the use of subjective rating scales of thermal perception, the use of photographs that assist thermal perception assessment, and survey-based elicitation of thermal perceptions. The approach that we propose can be easily scaled up across large samples of spatial points and a large number of participants. There are two potential benefits of this approach: 1) it can be used on a representative and large sample of spatial points representing a certain area (rather than on a set of arbitrarily selected spatial points), and 2) it can be administered to a large sample of participants representing a certain population (rather than convenience samples of participants).

We aim to partially validate this approach by showing that thermal perception ratings thus obtained are related to objective micro-climatic properties of places (average surface temperature) and that these ratings take into account place properties that are known to positively affect perceived thermal comfort (the presence of blue and green infrastructure). In addition, we also examine the predictive validity of long-term thermal perception ratings. Specifically, we are interested in whether average ratings of long-term thermal perceptions associated with places can predict outdoor activities (waiting and walking) in these places and preference for these places one year later.

### 5.1 Overview of studies

In Study 1, we conducted a survey of long-term thermal perception during summer heatwaves in the Czech city of České Budějovice and we looked at whether such thermal perception can be traced back to surface temperature, the presence of green and blue infrastructure, and the sky-view factor, as they should. Study 2 replicated the methodology in the Czech city of Brno. Finally, in Study 3, we looked at whether the long-term thermal perception measured in Study 2 was predictive of decision making regarding outdoor activities and place preference in the city of Brno one year later.

The case studies have been intentionally conducted in two typologically different cities. These differences concern climate, orography, and land cover. The city of Brno is located at the edge of the Pannonian biogeographical region. Summers are rather dry, with a sum of monthly precipitation of 60–80 mm, and hot, with the daily average temperature ranging between 21–23°C. The territory displays a significant orographic

variability (190–385 m asl) and this—together with extended impervious surfaces—causes most of the water from precipitations to be drained away without being absorbed and could potentially impact microclimate by latent heat. The city of České Budějovice has a continental climate, the sum of monthly summer precipitation is 90–100 mm, the summer daily average temperature ranges between 19–21°C. The orography is smooth, with an average altitude of 405 m asl. The most typical features of the city and the whole region are open water bodies, both rivers, and manufactured ponds. Because of extended areas of grasslands, precipitation water can be absorbed and impact the local microclimate. The differences in the land cover of the two experimental sites can be recognized in Figure 1.

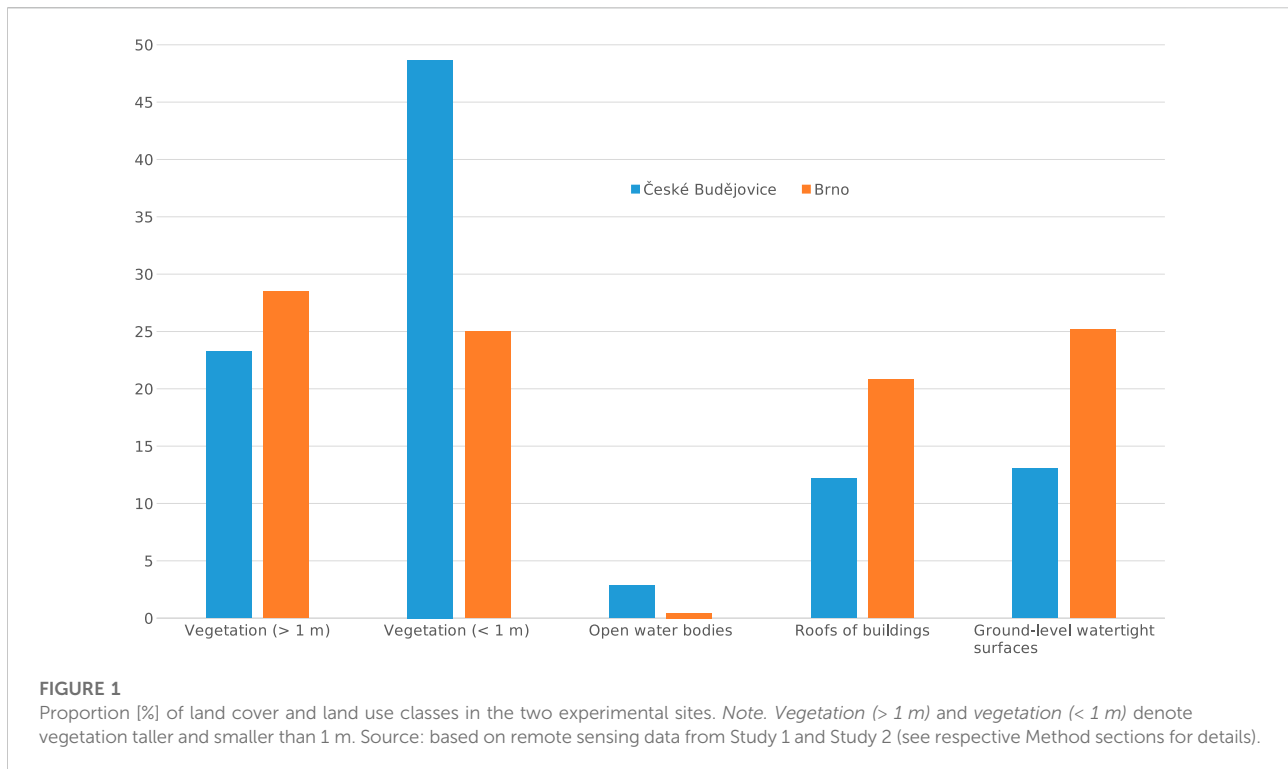
## 6 Study 1: Thermal perception and comfort in the city of České Budějovice

In Study 1 we look at whether a survey-based approach that uses rating scales to measure long-term thermal perception and perceived thermal comfort in combination with photographs of selected localities in the city of České Budějovice can provide measurements of long-term thermal perception and perceived thermal comfort. More specifically, we are interested in whether such measurements can be traced back to surface temperature, the presence of blue and green infrastructure, and the sky-view factor, which should theoretically affect long-term thermal perception and thermal comfort. In addition, we also wanted to know how well city residents can glean information about the presence of blue and green infrastructure from photographs of the places.

### 6.1 Method and procedure

#### 6.1.1 Participants

A sample of participants with permanent residency in the city of České Budějovice, recruited from a database of a marketing agency, was invited to participate in an online study; 483 participants entered the study and 336 (69.6%) completed it in July and August 2019. We have removed observations from two participants who received visual stimuli that we could not fully match with remote sensing data on the sampled locations (these 30 m buffers were not fully covered by remote sensing data). The final sample of participants ( $N = 334$ ) was fairly variable in terms of gender (74.5% were women), age ( $M = 37$ ,  $SD = 12.8$ ), and education (4.2% were people with primary education; 21.6% were people with secondary education without a high school diploma; 42.8% were people with a high school diploma; 31.4% were people with a university degree).



## 6.1.2 Materials

### 6.1.2.1 Development of visual stimuli

In České Budějovice, we defined a square encompassing a major part of the city; this square was defined by the coordinates E14.4255-14.5352, N48.940-49.0116 (see Figure 2). Note that we chose the square, rather than the administrative boundaries of the city because the square-shaped area was technically easier to sample spatial points from. Given that our aim here was to demonstrate a proof of the concept, rather than to generalize our results to administrative spatial units, this choice did not affect our conclusions.

Within this square, we randomly selected 2000 spatial points based on uniform distribution along the x- and y-axes. Using Google Street View Static API (Google Map, 2019b). Next, we searched the database of Google Street View to find the closest location within 20 m distance represented in the database. We found 799 locations that fulfilled these criteria (see Figure 2). For each of these locations, we downloaded, using Google API, four pictures from the Google Street View database showing northward, eastward, southward, and westward views from each location and we collated these pictures into one visual stimulus representing each location (see Figure 3 for an example of the stimuli). We then manually screened the photographs and excluded 58 pictures that depicted interiors of buildings, roads, highways, and overpasses where pedestrians cannot walk or stand nearby. The remaining set of 741 images

was selected to be used in data collection. In reality, 739 images were drawn randomly at least once during the survey process by the web-based questionnaire. However, we had to exclude another 13 visual stimuli that could not be correctly matched against the remotely sensed data because the remotely sensed data did not fully cover the 30 m buffer for these locations. The visual stimuli thus represented a fairly representative sample of publicly accessible outdoor places within the selected sub-section of the city of České Budějovice.

### 6.1.2.2 Remotely sensed independent variables

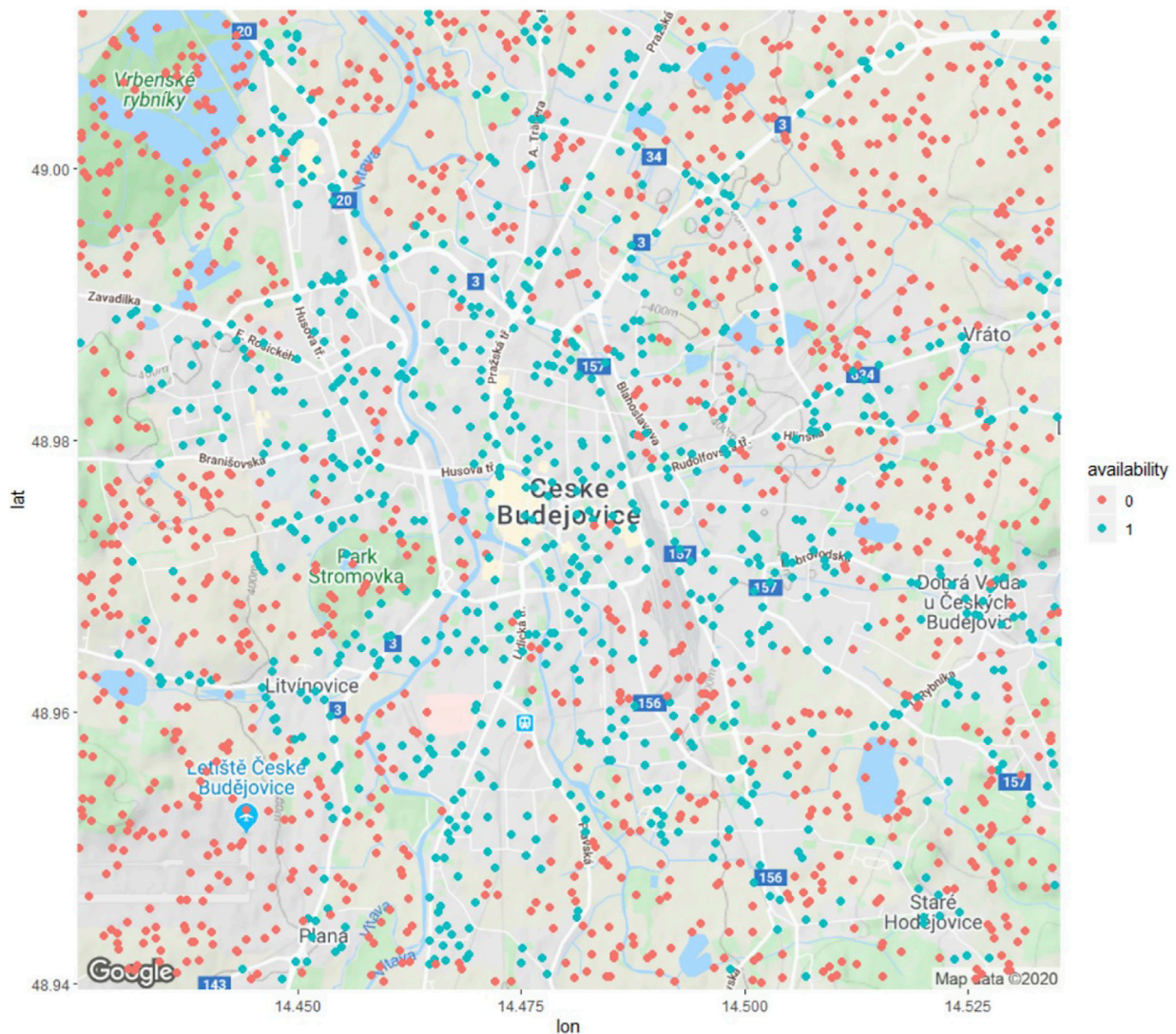
#### 6.1.2.2.1 Land cover classes

Two normalized differential vegetation indices (*VI*) were calculated from reflectance images as inputs to classification:

$$VI = \frac{(R_{B1} - R_{B2})}{(R_{B1} + R_{B2})}$$

Where  $R_{Bx}$  represents reflectance at wavelength  $Bx$ . The first *VI* used  $B1 = 800$  nm and  $B2 = 670$  nm and therefore corresponds to *NDVI* [23], commonly used to distinguish photosynthetically active vegetation. The second *VI* used  $B1 = 1,287$  nm and  $B2 = 1,512$  nm and enhanced differences in vegetation water content.

We classified the city's surface from *VI*s and normalized Digital Surface Model data into the following five classes: 1) roofs of buildings, 2) vegetation >1 m, 3) vegetation ≤1 m, 4) other impervious surfaces (e.g., roads), and 5) open water bodies. The



**FIGURE 2**

Availability of randomly selected locations in the Google Street View database (city of České Budějovice, Study 1). Note. Red and blue dots denote spatial points that were randomly selected within the square. Red dots denote locations that were not available in the database of Google Street View photographs, whereas blue dots denote locations that were available as Google Street View photographs and were used to develop visual stimuli for the current study.

classification was performed in the eCognition software (Trimble, Inc.) that uses an “object-oriented approach” to analyze images. The process comprises two steps. Firstly, the image is segmented into objects with a defined degree of homogeneity of input parameters. Secondly, the objects are categorized into classes following a programmed decision tree.

Our decision tree used normalized Digital Surface Model to separate high objects (trees, buildings) from objects with low height (low vegetation, roads), then the two vegetation indices enabled distinction between vegetation and other surfaces. The classification accuracy was evaluated on 800 randomly selected points, which were visually validated. Overall classification accuracy reached 84%.

In the current analysis, we used three land cover classes, namely classes of low and high vegetation (capturing presence of green infrastructure), and the open water body class (capturing presence of blue infrastructure). These indicators were computed as the proportion of pixels of respective class within a 30 m buffer. These indicators were standardized prior to analyses. However, we could not match 13 of the selected locations with remotely sensed data due to incomplete coverage of the 30 m buffers at these locations. Unmatched observations (57 out of the total of 5,010 observations given by the combination of 15 trials over 334 participants) were not used in the analysis.



**FIGURE 3**

Example of visual stimuli (city of České Budějovice, Study 1). Note. The four pictures (from top left to bottom right) capture, respectively, northward, eastward, southward, and westward views from the selected location.

#### 6.1.2.2.2 Land surface temperature

Land surfaces temperature image was obtained from the hyperspectral scanner TASI (8,000–11,000 nm). Data were acquired simultaneously with reflectance HS and LiDAR data. The radiometric and geometric preprocessing of thermal TASI data is identical to that of reflectance HS data. The calculation of land surface temperature (LST) is based on the Temperature and Emissivity Separation algorithm (TES, Pivovarnik et al., 2017). The measured radiance at sensor level ( $L_m$ ) mainly consists of radiance emitted from the land surface, downwelling atmospheric radiance reflected by the surface ( $L_{atm}^\downarrow$ ), and the atmospheric upwelling radiance ( $L_{atm}^\uparrow$ ). The sum of all these components is expressed by a radiative transfer equation (RTE) as follows:

$$L_m = \tau \epsilon B(T_s) + \tau(1 - \epsilon)L_{atm}^\downarrow + L_{atm}^\uparrow \quad (1)$$

where  $B(T_s)$  is the radiance of the surface at temperature  $T_s$  according to Planck's law,  $\epsilon$  is the surface's emissivity, and  $\tau$  is the atmospheric transmittance. The atmospheric parameters,  $L_{atm}^\downarrow$ ,

$L_{atm}^\uparrow$ , and  $\tau$  are modeled using the MODTRAN 5.3 radiation transfer model. The TES is based on the similarity between brightness temperature spectral features and emissivity spectral features. It uses an iterative process in estimating spectral emissivity and the respective temperatures. The calculus minimizes a difference between the black body radiance curve and the curve of spectral radiance obtained for given emissivity and temperature.

#### 6.1.2.2.3 The sky-view factor

The sky-view factor was computed as a percentage of hemisphere representing the sky in SAGA GIS software (Conrad et al., 2015) from the digital surface model interpolated from the LiDAR data with a very high spatial resolution (0.25 m).

We used zonal statistics to calculate the number of pixels of each land cover class within a buffer zone of diameter 30 m around the target position, the average surface temperature of a

zone, and the sky-view factor as the mean value of the sky-view factor from ground pixels (pixels classified as vegetation <1 m, impervious surfaces and water bodies). The sky-view factor was standardized before analyses.

### 6.1.2.3 Dependent variables based on survey responses

#### 6.1.2.3.1 Rating of thermal perception

Participants assessed sequentially their long-term thermal perception at 15 randomly selected locations shown on visual stimuli. Specifically, participants indicated how they would describe the temperature that they would feel at each location “during a heatwave” using a seven point scale with seven labelled points (*cool, slightly cool, neutral, slightly warm, warm, hot, extremely hot*). Our scale was derived from the ASHRAE scale of thermal perception. The only difference was that in our scale, we added one point (extremely hot), and we removed one point (cold) from the original scale to allow for better differentiation in the higher thermal perception levels that we expected given that participants estimated their thermal perception during a heatwave. Note that this methodological decision was vindicated by the fact that the lowest category on our scale (*cool*) was used extremely rarely (0.9% of ratings), whereas the two highest categories were used frequently (*hot* in 27.0% of cases and *extremely hot* in 16.4% of cases).

#### 6.1.2.3.2 Rating of thermal comfort

Participants used the same 15 randomly selected stimuli as in the thermal comfort measure but this time they sequentially rated how they would feel overall at the location shown in the stimulus during a heatwave using a seven-point scale (*extremely uncomfortable, very uncomfortable, uncomfortable, neutral, pleasant, very pleasant, extremely pleasant*).

### 6.1.2.4 Perceived properties of sampled locations

For the set of photographs of target points from České Budějovice, we performed manual coding of their content. Three coders evaluated six attributes of the photographs (whether the sky in the image is cloudy, whether there are bodies of water in the image, whether there are trees within 30 m distance, whether there are trees within 5 m, whether there is grass or shrubs within 5 m, and whether the location is shaded during the day by an artificial structure). Each attribute was independently rated by two coders, and if they disagreed, we used a third coder’s rating for that photograph. Inter-rater variability (i.e., inter-rater correlation of ratings) was moderate or reduced for all attributes: cloud cover rating,  $irr = 0.83$ ; presence of water bodies,  $irr = 0.80$ ; presence of trees,  $irr = 0.64$ ; presence of nearby trees,  $irr = 0.63$ ; presence of shrubs,  $irr = 0.62$ ; presence of artificial shading,  $irr = 0.25$ . These results suggest that different people can identify blue and green

infrastructure, and shading structures in the pictures rather similarly.

### 6.1.3 Procedure

After giving informed consent, each participant browsed a set of 15 randomly selected images of sampled locations in České Budějovice taken from Google Street View and indicated for each location whether they had ever been to that location. Subsequently, for the same 15-point images, participants rated the perceived heat they would feel at that location during a heatwave. Subsequently, participants rated, for the same 15 locations, how they would feel overall at that location during a heatwave. At the end of the questionnaire, participants answered two questions assessing subjective attention and concentration and three demographic questions (gender, age, education). Upon completion of the study, participants were directed to the web page of the opinion poll company, and they received a small reward for their participation in the study (20 CZK; equivalent to \$0.85).

### 6.1.4 Analyses

We used correlational analysis to check the match between perceived properties and remotely sensed properties of sampled locations. This analysis shows whether people can glean information about the presence of blue and green infrastructure and exposure to the Sun from our visual stimuli. Further, we used a mixed ordinal logit model to analyze whether subjective ratings of long-term thermal perception and thermal comfort can be related to surface temperature, the presence of blue and green infrastructure, and the sky-view factor, as they theoretically should.

## 6.2 Results

### 6.2.1 Relationship between remotely sensed and perceived place attributes

Perceived attributes of each point determined by independent coders from pictures correlated with attributes of those points derived through methods of remote sensing regarding the presence of trees,  $r_{pb} = 0.46$  (point biserial correlation), presence of bush and shrub,  $r_{pb} = 0.48$ , presence of water bodies,  $r_{pb} = 0.70$ , and presence of obstacles that shade the area (i.e., with remotely-sensed sky-view factor),  $r_{pb} = -0.50$ , all  $ps < 0.001$ . Expectedly, there was no relationship between sky cloudiness observed by coders on the visual stimuli and the mean direct irradiation recorded for each location by remote sensing, as the two sets of observations were made on different days.  $r_{pb} = 0.03$ ,  $p = 0.380$ . This was the reason why we did not include remotely sensed indicator of cloudiness (i.e., proxied by inverse of the direct irradiation) in our main models reported in the next two sections.



TABLE 1 Models of thermal perception and thermal comfort (mixed ordinal logit Model, city of České Budějovice, Study 1).

	Thermal perception				Thermal comfort			
	Reduced model		Full model		Reduced model		Full model	
	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
<i>Effects of remotely sensed variables</i>								
Surface temp	0.08	<0.001	0.03	0.166	-0.11	<0.001	-0.04	0.045
Trees			-0.22	0.001			0.26	<0.001
Bushes			-0.16	0.009			0.16	0.007
Water			-0.04	0.410			0.09	0.037
Sky-view factor			0.14	0.008			-0.21	<0.001
<i>Model properties</i>								
Nobs	4,953		4,953		4,953		4,953	
Log likelihood	-7,703		-7,671		-7,532		-7,477	
Conditional R2	0.367		0.373		0.366		0.375	
Marginal R2	0.021		0.034		0.035		0.056	

Note. DVs, are thermal perception (higher scores indicate higher level of perceived heat) and thermal comfort (higher scores indicate a higher level of thermal comfort) at the place during a hot day. *Surface temp.* Is the average land surface temperature (deg C) inside a 30 m buffer. The following independent variables were measured as the proportion of pixels within a 30 m buffer around the sampled locations that were classified into the following land cover types: *trees* (vegetation higher than 1 m), *bushes* (vegetation smaller than 1 m), water (any water elements such as rivers, streams, ponds). To avoid singularity of the model, we have not included watertight surfaces (including building roofs) in the model. *Sky-view factor* is the estimated sky-view factor at each sampled location. *Nobs* is the number of observations across participants and trials (334 × 15), minus 57 observations that cannot be matched against complete remotely sensed data. *Log likelihood* is the log-likelihood value of the model. *Conditional R2* is the variance explained by fixed and random effects, *marginal R2* is the variance explained by the fixed effects. Six ordinal thresholds and two random intercepts were omitted.

## 6.2.2 Thermal perception

As theoretically expected, the mixed ordinal logit model revealed that people's subjective rating of long-term thermal perception at the sampled location was positively affected by land surface temperature based on remote sensing (see estimates of the reduced model in Table 1 for details). Importantly, the effect of surface temperature on long-term thermal perception was completely mediated by the presence of green and blue infrastructure and presence of shading elements (captured by the sky-view factor) as indicated by the fact that when these attributes were introduced in the model, the effect of surface temperature on thermal perception dropped significantly and became statistically insignificant (see estimates of the full model in Table 1 for details). This result suggests that survey participants used the presence of blue and green infrastructure and the presence of shading elements as cues that help them to determine their long-term thermal perception in each of the places. This interpretation is further supported by the fact that the presence of trees and bushes had the expected negative effect on thermal perception, whereas the sky-view factor had a positive effect on thermal perception. The presence of water did not have a statistically significant effect on thermal perception, probably due to the relative scarcity of blue infrastructure in sampled locations (see Supplementary

Table SA1 in the Appendix for descriptives of independent variables).

Importantly, we were able to partly corroborate the main results on a sub-sample of observations from participants who had little or no prior experience with the sampled locations and who had not visited them in the last year (79.1% of observations). Specifically, even these participants reported long-term thermal perception that matched remotely sensed surface temperature (see the reduced model in Supplementary Table SA2 for details). However, this relationship disappeared once we added remotely sensed indicators of the presence of the green and blue infrastructure and the sky-view factor in the model (see the reduced model in Supplementary Table SA2 for details). Again, this result suggests that people tend to estimate their long-term thermal perception using available visual cues, such as the presence of green and blue infrastructure and the presence of shading elements (inversely related to the sky-view factor). Indeed, the presence of trees had the expected negative effect whereas the sky-view factor had the expected positive effect on long-term thermal perception. The presence of bushes and water elements had no statistically significant effect on long-term thermal perception possibly due to the smaller size of the sub-sample which might have reduced the statistical power of the study.

### 6.2.3 Thermal comfort

The mixed ordinal logit model also revealed the theoretically expected negative effect of surface temperature (based on remote sensing) on the rating of expected thermal comfort (based on survey data; for details, see the reduced model in [Table 1](#)). This effect was partially mediated by the presence of blue and green infrastructure and the presence of shading elements (inversely related to the sky-view factor), suggesting, again, that participants estimated their expected thermal comfort based on visual cues available in the visual stimuli (i.e., presence of blue and green infrastructure and presence of shading elements). This conclusion is further supported by the fact that the presence of trees, bushes, and water and the sky-view factor are all statistically significantly related to the expected thermal comfort expressed by participants (see the full model in [Table 1](#)). Note that all these substantial results hold when the model is estimated on a sub-sample of observations from participants who have not visited these locations (for details, see [Supplementary Table SA2](#)).

## 6.3 Discussion of study 1

We corroborated in Study 1 that people use visual cues present in photographs of locations, such as the presence of blue and green infrastructure and the presence of shading elements to determine their long-term thermal perception and expected thermal comfort at each location during a hot day. These subjective judgments match objective properties of these locations (based on remote sensing data) that are known to affect thermal perception and comfort, such as land surface temperature, the presence of blue and green infrastructure, and shading of locations.

## 7 Study 2: Thermal perception in the city of Brno

Study 1 used a relatively small number of sampled locations and individual participants, potentially decreasing the statistical power of the study. In Study 2 we aimed to replicate the results from Study 1 using data from a larger sample of locations from the city of Brno and a larger sample of participants (Brno residents).

## 7.1 Method and procedure

### 7.1.1 Participants

A sample of participants with permanent residency in the city of Brno, recruited from a database of a marketing agency, was invited to participate in an online study; 925 participants entered

the study and 615 (66.5%) completed it in July and August 2019. The final sample of participants was fairly variable in terms of age ( $M = 37.2$ ;  $SD = 12.5$ ), gender (71.6% were women), and education (4.1% were people with primary education; 17.3% were people with secondary education without a high school diploma; 47.5% were people with a high school diploma; 31.1% were people with a university degree).

## 7.1.2 Materials

### 7.1.2.1 Development of visual stimuli

Similar to Study 1, we defined a square encompassing the wider city center of Brno; this square was defined by the coordinates E 16.552–16.66175, N 49.1592–49.2308 (see [Figure 4](#)). Within this square, we randomly selected (without replacement) 2000 spatial points; the uniform distribution of point selection probabilities along the x- and y-axes resulted in each point in the square having the same selection probability. Using Google Street View Static API ([Google Map, 2019a](#)), we searched the database of Google Street View pictures to find a picture that would represent this point or a nearest point within 20 m distance. Google Street View was available for 1,272 points. We manually screened the photographs and excluded 142 pictures that depicted interiors of buildings, roads, highways and overpasses where pedestrians cannot walk or stand nearby. The remaining set of 1,130 pictures was used as stimuli in data collection. The stimuli were processed as in Study 1 by collating the four views from each location (see [Figure 5](#) for an example of the stimuli).

### 7.1.2.2 Measures

We used the same measures as in Study 1.

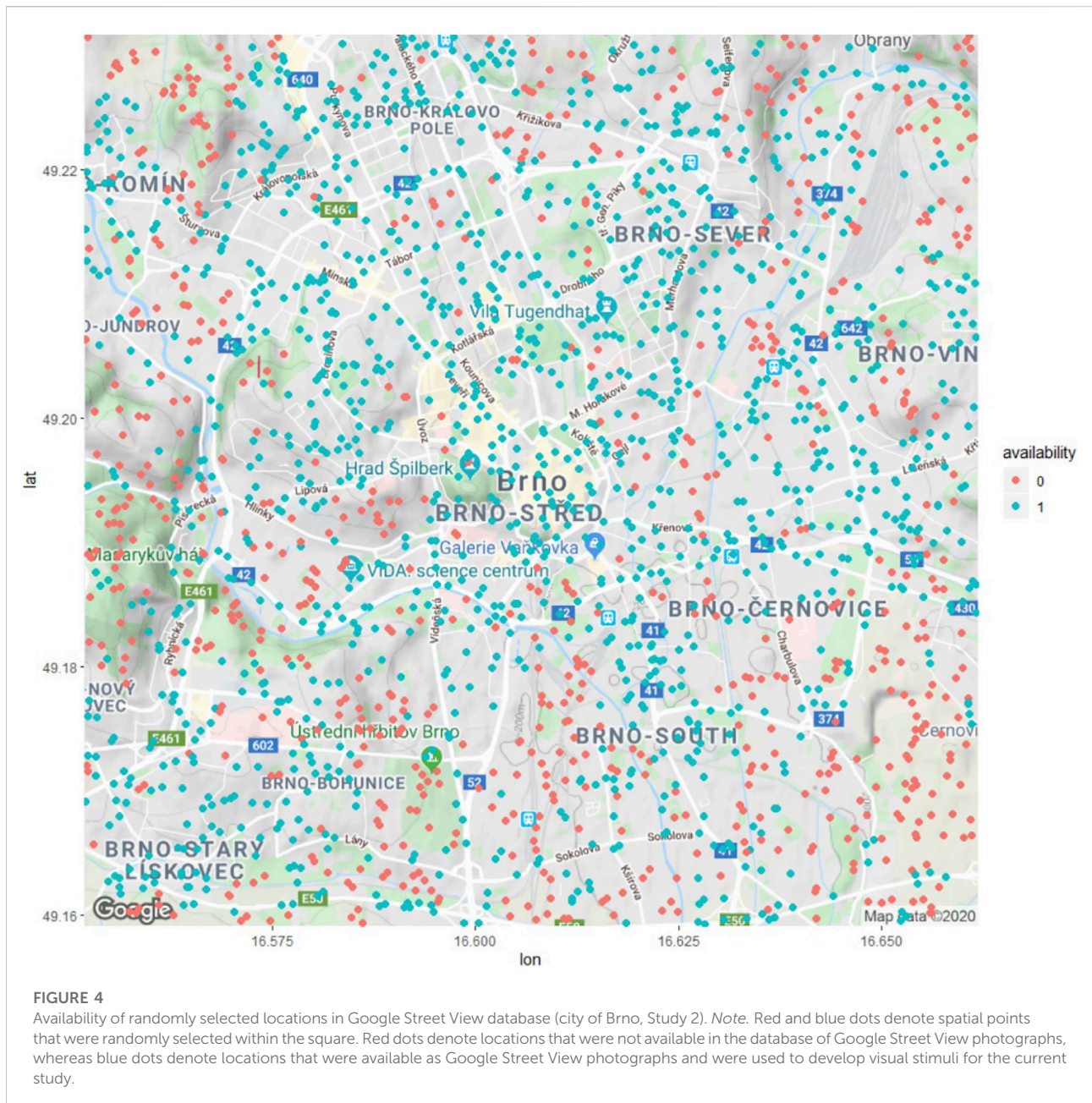
### 7.1.3 Procedure and analyses

We used the same procedure and analyses as in Study 1.

## 7.2 Results

### 7.2.1 Relationship between remotely sensed and perceived place attributes

Perceived attributes of each point determined by independent coders from pictures correlated with attributes of those points derived through methods of remote sensing regarding the presence of trees,  $r_{pb} = 0.47$  (point biserial correlation), presence of bush and shrub,  $r_{pb} = 0.40$ , presence of water,  $r_{pb} = 0.46$ , and presence of obstacles that shade the area (i.e., with remotely-sensed sky-view factor),  $r_{pb} = -0.52$  all  $ps < 0.001$ . Expectedly, there was a relatively small match between mean direct irradiation at the moment of taking the remotely sensed data and rating of cloudiness on pictures of locations by raters,  $r_{pb} = -0.12$ ,  $p < 0.001$ , due to the fact that the two measurements capture different moments with different cloudiness. This was the reason why we did not include the remotely sensed



indicator of cloudiness (i.e., proportional to the inverse of the direct irradiation) in our main model, similarly to Study 1.

### 7.2.2 Thermal perception

The results of Study 2 fully corroborated the results of Study 1. Specifically, we observed the theoretically expected positive relationship between (remotely sensed) surface temperature and (subjective survey-based) long-term thermal perception (for details, see the reduced model in Table 2). However, a large part of this relationship was mediated by the presence of blue and green infrastructure

and the sky-view factor, suggesting that people used these attributes as visual cues when inspecting the visual stimuli and determining their long-term perceived thermal comfort at each location (for details, see the full model in Table 2). This conclusion is supported also by the fact that all remotely sensed characteristics of locations included in the model (i.e., presence of trees and bushes, presence of water, and sky-view factor) had theoretically expected effects on the subjective long-term thermal perception.

Importantly, the model estimated on the sub-sample of participants who had little or no experience with respective



**FIGURE 5**

Example of visual stimuli (city of Brno, Study 2). *Note.* The four pictures (from top left to bottom right) capture, respectively, northward, eastward, southward, and westward views from the selected location.

locations and did not visit them in the last year (85.5% of observations) revealed essentially the same results (for details, see [Supplementary Table SA4](#)). This means that people were able to infer from pictures of locations rather than from their personal experience information that they used to estimate their long-term thermal perception.

Taken together, these results suggest, once again, that visual cues available in photographs of locations allow people to estimate their long-term thermal perception at each sampled location that matches thermal patterns (surface temperature) that we objectively observe at these locations (through remote sensing).

### 7.2.3 Thermal comfort

We were also able to corroborate the results of Study 1 concerning thermal comfort. Again, we found that the (remotely sensed) surface temperature was negatively related to (subjective survey-based) perceived thermal comfort (for details, see the reduced model in [Table 2](#)). This relationship was

considerably reduced when (remotely-sensed) indicators capturing the presence of green and blue infrastructure and the sky-view factor were introduced in the model (for details, see the full model in [Table 2](#)). This observation suggests that participants based their judgment of perceived thermal comfort on visual cues available in the pictures, namely the presence of blue and green infrastructure and the presence of shading elements. This conjecture is further supported by the fact that (remotely sensed) presence of bushes, trees and water as well as the sky-view factor all had the theoretically expected effect on (subjective survey-based) thermal comfort. Additionally, this conclusion is also supported by the fact that the same substantial results were obtained on a sub-sample of observations from participants who had little or no direct experience with respective locations (for details, see [Supplementary Table SA4](#)).

Taken together, these results suggest, once again, that people base their subjective rating of expected perceived thermal comfort on visual cues that are available in photographs of target locations. More importantly, we found that these subjective expectations match objective thermal properties (surface temperature) across the locations.

TABLE 2 Models of thermal perception and thermal comfort (mixed ordinal logit Model, city of Brno, Study 2).

	Thermal perception				Thermal comfort			
	Reduced model		Full model		Reduced model		Full model	
	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$	$\beta$	$p$
<i>Effects of remotely sensed variables</i>								
Surface temp	0.10	<0.001	0.02	0.032	-0.18	<0.001	-0.03	0.013
Trees			-0.37	<0.001			0.38	<0.001
Bushes			-0.16	<0.001			0.25	<0.001
Water			-0.09	0.004			0.18	<0.001
Sky-view factor			0.45	<0.001			-0.60	<0.001
<i>Model properties</i>								
Nobs	9,225		9,225		9,225		9,225	
Log likelihood	-13641		-13429		-13628		-13431	
Conditional R2	0.477		0.488		0.584		0.541	
Marginal R2	0.021		0.086		0.049		0.113	

Note. DVs, are thermal perception (higher scores indicate higher level of perceived heat) and thermal comfort (higher scores indicate a higher level of thermal comfort) at the place during a hot day. *Surface temp.* Is the average land surface temperature (deg C) inside a 30 m buffer. The following independent variables were measured as the number of pixels within a 30 m buffer around the sampled locations that were classified into the following land cover types: *trees* (vegetation higher than 1 m), *bushes* (vegetation smaller than 1 m), water (any water elements such as rivers, streams, ponds). *Sky-view factor* is the estimated sky-view factor at each sampled location. *Nobs* is the number of observations (615 participants x 15 trials). *Log likelihood* is the log-likelihood value of the model. *Conditional R2* is the variance explained by fixed and random effects, *marginal R2* is the variance explained by the fixed effects. Six ordinal thresholds and two random intercepts were omitted.

## 7.3 Discussion of study 2

In Study 2, we corroborated results from Study 1 using a large dataset of target location and participants from the city of Brno. Specifically, we found, as in Study 1, that people can very well glean from photographs information about the properties of those locations that should theoretically affect their thermal perception and comfort such as exposure to the Sun and the presence of blue and green infrastructure. We also corroborated that people's subjective rating of long-term thermal perception and comfort at the sampled locations reflects the objective thermal properties of these places (remotely sensed surface temperature).

## 8 Study 3: Thermal perception and decision making in the city of Brno

In Study 3 we look at whether long-term thermal perceptions associated with certain locations are useful for the prediction of pedestrians' behavior in those locations. Specifically, we are interested in whether the average long-term thermal perceptions associated with specific spatial points collected in Study 2 can be used to predict the choice of a walking route, choice of a waiting place, and the preference of a place in a new sample of participants more than one year later.

## 8.1 Method

### 8.1.1 Participants

The participants of the study were all residents of Brno. Participants were recruited in November and December 2020 based on quota characteristics from a participant panel of an opinion poll company. The study recruited 1,099 participants, of whom 865 completed the study (78.7% completion rate). We excluded 2 participants for whom the data was incomplete due to technical error, resulting in a sample size of  $N = 863$  participants. The sample of participants was fairly variable in terms of age ( $M = 40.4$ ;  $SD = 13.4$ ), gender (56.2% were women), and education (6.0% were people with primary education; 22.0% were people with secondary education without a high school diploma; 42.5% were people with a high school diploma; 29.5% were people with a university degree).

### 8.1.2 Materials

#### 8.1.2.1 Independent variable

Average long-term thermal perception. Based on participants' rating of their thermal perception in Study 2, we computed the average thermal perception rating of each of the 1,130 spatial points in the city of Brno featured in Study 2.



### 8.1.2.1 Dependent variables

**Place preference for walking.** We measured place preference for walking with a choice experiment. The choice experiment had 15 trials. Each trial of the choice experiment consisted of pairs of photographs depicting two randomly selected locations (northward view) from the database of 1,130 locations in the city of Brno used in Study 2. The photographs were arranged side by side (see Figure 6 for an example of the stimuli). In each trial, participants selected one place from the pair where they would “prefer to walk on a very hot day.”

**Place preference for waiting.** We measured place preference for waiting with a similar choice experiment (using the same set of randomly chosen photograph pairs) as place preference for walking, except that participants selected in each trial a place where they would “prefer to wait for somebody on a very hot day.”

**Thermal comfort preference.** We measured the thermal comfort preference using a choice experiment, similar to walking and waiting place preference. The only difference was that participants selected in each trial a place where they would “feel better on a very hot day.”

### 8.1.3 Procedure

Study participants received a personalized invitation to enter an online study. Before entering the study, prospective participants indicated whether they lived in the Brno district or elsewhere. Only those who indicated the Brno-City district as their place of residence were allowed to enter the study. After providing informed consent, a set of 15 stimuli for the choice experiment was randomly generated for each participant for use in the three choice experiment tasks.

Subsequently, participants went through 15 trials of the walking preference task, 15 trials of the place preference task, and 15 trials of the thermal comfort preference task. At the conclusion of the study, participants provided basic demographic information (gender, age, and education), identified their area of residence via zip code, and answered two self-assessment questions (attention to instructions and accuracy of responses). Upon completion of the study, participants were directed to the web page of the opinion poll company and they received a small reward for their participation in the study (20 CZK; equivalent to \$0.85).

### 8.1.4 Analyses

We used mixed binary logit models to analyze each of the three choice experiment tasks. These models had the place preferences as dependent variables and average thermal comfort ratings from Study 2, associated with each location, as their independent variable. The model also included random intercepts that captured idiosyncratic effects of each choice set. Besides estimating the effects of the thermal preference ratings on place preference, we also estimated how well one can predict people’s behavior based on such a model.

## 8.2 Results

### 8.2.1 Place preference for walking

Using the mixed logit model, we found that the average thermal perception from Study 2, associated with each place,

**TABLE 3** Model of the preference of walking route, waiting place, and choice of the place where one would feel better (mixed binary logit models, city of Brno, Study 3).

	Walking		Waiting		Feeling	
	$\beta$	<i>p</i>	$\beta$	<i>p</i>	$\beta$	<i>p</i>
<i>Model estimates</i>						
Intercept	3.57	<0.001	3.15	<0.001	3.42	<0.001
Average thermal comfort	-0.70	<0.001	-0.62	<0.001	-0.67	<0.001
<i>Model properties</i>						
Nobs	25,890		25,890		25,890	
Log likelihood	-16230		-16429		-16342	
<i>Explained variance</i>						
Conditional R2	0.24		0.22		0.23	
Marginal R2	0.07		0.06		0.07	
<i>Outcome prediction</i>						
Accuracy	0.69		0.69		0.69	

*Note.* DVs, are: choice of walking route, choice of waiting place, and choice of place where one would feel better. *Average thermal comfort* is the average thermal comfort associated with each of the target places based on participants' ratings in Study 2. *Nobs* is the number of observations (863 participants x 15 trials x 2 possible place preferences). *Log likelihood* is the log-likelihood value of the model. Conditional R2 is the variance explained by fixed and random effects, marginal R2 is the variance explained by the fixed effects. *Accuracy* is the overall rate of successful predictions of participants' choices based on the model.

had the expected negative effect on the choice of the walking route (see Table 3 for details). In other words, the average long-term thermal perceptions associated with each place and captured in Study 2 predicted how different people one year later preferred these places for walking. Importantly, such a model has 69% accuracy. This means that the model can correctly predict 69% of behavioral choices regarding the choice of walking route.

### 8.2.2 Place preference for waiting

Using a similar model as for walking preference, we found that the average thermal perception also had the expected negative effect on waiting place preference (see Table 3 for details). In other words, the hotter the place was perceived by participants in Study 2, the less likely were participants in Study 3 to choose it as a waiting place. Again, the model correctly predicted about 69% of behavioral choices regarding the choice of waiting place.

### 8.2.3 Thermal comfort preference

Finally, using a similar model as we used for the waiting and walking tasks, we found that average thermal perception also has the expected negative effect on where people think they would feel better (see Table 3 for details). Again, this means that average long-term perceptions associated with each place were predictive of where people would feel better. The accuracy of such a prediction was 69%.

## 8.3 Discussion of study 3

In Study 3, we found that long-term thermal perceptions associated with specific places in the city of Brno and estimated on one sample of participants during a heatwave predicted how a different group of people preferred these places one year later for activities such as walking and waiting, and where they would feel better on an extremely hot day. These results suggest that subjective ratings of expected thermal perception are valid predictors of human behavior, as we would theoretically expect them to be.

## 9 General discussion

This study aimed to present and partially validate an approach to assessment of outdoor long-term thermal perception and comfort in urban environments. This approach combines some techniques previously used in thermal perception assessment, namely subjective rating scales, off-site survey administration, and representation of specific urban locations with photographs.

Across three studies conducted in two Czech cities, we found some preliminary evidence that long-term thermal perception and comfort elicited through a combination of these techniques is theoretically valid and practically useful. Specifically, in two of the studies, we were able to corroborate that photographs of

urban locations are sufficient to convey information about the properties of urban locations, such as the sky-view factor and the presence of blue and green infrastructures, upon which people based their long-term thermal perception. More importantly, we saw that long-term thermal perception elicited through this approach is related in a theoretically expected way to objective thermal properties of these places (remotely sensed surface temperature) and to properties of these places that affect local micro-climate (sky-view factor, and the presence of blue and green infrastructure).

Finally, and perhaps most importantly, we also demonstrated that long-term thermal perception is useful practically as it can predict mundane outdoor behavior such as choice of waiting place or preference for a walking route. Specifically, we showed that thermal perception associated with specific places and derived using one sample of participants can be used to predict mundane outdoor activities in the very same places of a different group of people more than one year later.

## 9.1 Validity of thermal perception

Obviously, our study could only provide limited evidence of the validity of what we can call a photographic method of long-term thermal perception assessment. It is rather obvious that the task that our participants were accomplishing by trying to rate their thermal expectations associated with specific urban locations “during a heatwave” or “on a very hot day” is cognitively demanding. However, the literature shows that people are skilled in inferring thermal properties from subtle cues that visual inspection of environments can provide (Lenzholzer, 2010). This is not so surprising if we consider that the human ability to predict how one would feel in different environments under different conditions was key to the human ability to adapt to and survive in harsh environments.

We can hypothesize that it is this cognitive ability to predict one’s thermal perceptions that makes long-term thermal expectations so useful in the prediction of human outdoor behavior. As a result, average thermal expectations associated with some locations in one group of people can explain the outdoor behavior of a different group of people more than one year later, as we have seen in one of our studies.

We think that the photographic approach to thermal perception assessment can be used to complement other methods of thermal perception assessment. This can be particularly useful in situations where we want to know how certain (and potentially large) populations of people perceive thermal comfort in a large number of locations. Such tasks are typically addressed with cognitive mapping approaches but these are known to be biased and tend to oversample locations associated with extreme thermal perceptions (Lehnert et al., 2021).

## 9.2 Practical implications

Long-term thermal perception is recognized as an important factor that determines people’s outdoor behavior (e.g., Lenzholzer, 2010). One of our studies supports this conclusion by showing that long-term thermal perception predicts how people prefer specific urban locations for walking and waiting. Obviously, these are just two of many examples of outdoor activities that are potentially affected by people’s thermal expectations. As such, knowing long-term thermal expectations regarding different locations under different conditions (e.g., time of the year, occurrence of extreme weather events) can be useful for understanding and predicting human outdoor behavior in urban settings. As such, long-term thermal expectations can provide important input for urban planners.

## 9.3 Limitations and avenues for future research

One of the challenges for any study that tries to elicit people’s long-term thermal perceptions and thermal comfort associated with specific places is that such studies must ask people to imagine specific conditions that apply to these thermal perceptions and thermal comfort. For instance, in our study, we asked participants to imagine how they would feel at each location on “a very hot summer day”. Arguably, each person has a slightly different idea of what “a very hot day” means. Such idiosyncratic inter-personal differences undoubtedly introduce random error in persons’ responses. However, as our studies show, the ratio of this error to the measured quantity (i.e., rating of thermal perception and rating of thermal comfort) has to be relatively low because we were still able to reveal the theoretically expected relationship between people’s subjective perceptions and objective thermal properties of these places (i.e., remotely sensed surface temperature on a hot day) and the presence of (remotely sensed) blue and green infrastructure and sky-view factor. Thus, even with the measurement error that is necessarily associated with the elicitation of subjective thermal perceptions, such have enough precision to be useful to meaningfully compare specific urban locations.

Given that the present study could only provide limited evidence of the validity of the photographic approach to thermal perception assessment, future studies should seek to provide additional validity checks of this method. For instance, the results from the current approach can be cross-checked with results from *in-situ* measurements of thermal perception and with cognitive mapping. Further, the temporal stability of long-term thermal perception in persons should be studied.

Another limitation of our study is that we did not explore the mechanism through which people arrive at the thermal perception assessments when observing visual stimuli. While we know that people infer their thermal expectations from visual cues available in locations, experiments that would manipulate



these properties can shed more light on how people arrive at their long-term thermal perceptions.

Another limitation of the current study is that it only focused on three behavioral outcomes affected by long-term thermal perception, namely preference of place for walking, waiting, and overall place preference. Future studies may focus on other types of outdoor behavior and use methods, such as experience sampling (Bolger and Laurenceau, 2013) that allow for a study of human behavior in realistic and dynamic settings.

Finally, the current study is also limited in that it covers only two Czech cities. Future studies may explore the generalizability of our approach in different urban, climatic, and cultural contexts. For instance, cultural differences are known to play a significant role in thermal perception (Chen and Ng, 2012). Thus, using the current photographic method in varied cultural contexts can help us to understand the limits of its generalizability.

## 10 Conclusion

We presented and partially validated a photographic approach to assessment of long-term outdoor thermal perception and comfort related to heatwaves in urban environments. This approach combines subjective rating scales, off-site survey administration, and representation of specific urban locations with photographs. As such, this approach is suitable for the assessment of how a large group of people perceives thermal comfort in a large number of places during heatwaves. Measurements of the long-term thermal perception and comfort based on this approach are related to theoretically known predictors of thermal perception and thermal comfort. Moreover, such measures are also predictive of outdoor activities. This approach to thermal perception and assessment can complement similar existing methods such as cognitive mapping.

## Data availability statement

The datasets and analytical scripts used for analyses presented in this study can be found in an online repository at: <https://osf.io/qw9fg/>.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and

institutional requirements. The participants provided their implicit informed consent to participate in this study.

## Author contributions

JU: Conceptualization, data curation, formal analysis, investigation; methodology, writing–original draft; MP: Data curation, formal analysis, investigation, writing–review and editing. FZ: Funding acquisition, project administration, investigation, formal analysis, writing–review and editing. JN: Investigation, formal analysis, writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.878341/full#supplementary-material>

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