Energy & Buildings 256 (2022) 111757

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Meta-analysis of outdoor thermal comfort surveys in different European cities using the RUROS database: The role of background climate and gender

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ARTICLE INFO

Article history:
Received 8 June 2021
Revised 25 November 2021
Accepted 30 November 2021
Available online 04 December 2021

Keywords:
Physiologically equivalent temperature
Neutral temperature
Sun preference
Gender differences
Thermal adaptation

ABSTRACT

Systematic comparisons of subjective thermal assessments among different geographical locations and between different genders are quite limited. This paper presents a *meta*-analysis using the data of comprehensive European outdoor thermal comfort (OTC) surveys. The aim is to reveal the common traits and the major differences regarding the subjective thermal perception and sun preference of residents in different European cities while taking great emphasis on the role of genders. The analysis relies on the RUROS (Rediscovering the Urban Realm and Open Spaces) project which was conducted in seven European cities, and the Hungarian OTC project. Only acclimatized local residents were considered to reflect the geographical and possibly cultural differences among the population of the investigated cities. The resulted neutral temperature values – expressed in terms of Physiologically Equivalent Temperature (*PET*) and determined by means of regression analysis – showed strong correlation with the long-term climatic characteristics, and narrower neutral zone was found at those locations where the annual temperature amplitude was small. Inhabitants of sunny and warm cities did not prefer more sunshine even when the actual sunshine value was low, while where the annual amount of sunshine was low the people showed greater sun preference. European women were found to perceive the thermal conditions as neutral under slightly warmer conditions than men and showed greater sensitivity to the changes of the environmental conditions. This was evidenced by narrower neutral *PET* zone of females and stronger correlation between their sun preference and the actual value of solar radiation.

1. Introduction

Outdoor thermal comfort (OTC) has drawn wide attention in the context of rapid urbanization and global climate change, especially since the last decade [4,17,42]. A generally adopted evaluation protocol of outdoor thermal conditions is based on well-established human-biometeorological indices – such as the Physiologically Equivalent Temperature (*PET*) [34,15] or the Universal Thermal Climate Index (*UTCI*) [3] – and their threshold values indicating different grades of thermal stress and/or human thermal perception. The indices are used to describe the physiological effect of the thermal environment (determined by the combination of local meteorological parameters including radiant fluxes, air temperature, humidity and wind speed) on a general human subject; for example in the case of *PET*, on a 35 year old, 1.75 m, 75 kg male in light clothing (0.9 clo) who performs light activity (80 W) [15]. However, because of these standardized personal parameters the obtained index values cannot be regarded universal for everybody, particularly when considering the American Society for Heating, Refrigerating and Air-conditioning Engineers definition for comfort as that "state of mind, which expresses satisfaction with the thermal environment" [1]. Accordingly, subjective evaluation of people is essential which can be obtained through questionnaire surveys, when people are asked to indicate their personal thermal perception (called thermal sensation in several studies), thermal preference, level of thermal comfort or thermal acceptability (e.g., [22,23,16,12,30,17]).

Increasingly, it is accepted that OTC is influenced not only by environmental stimuli, but also by personal, cultural, as well as psychological factors [40,9,11,25]. For example, one of the most

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https://doi.org/10.1016/j.enbuild.2021.111757
0378-7788/

important subjective indicators of thermal comfort, the neutral temperature, i.e., when people feel neither cold nor warm has been found to be significantly different among different countries and regions [38,19,10,54,41] provide a comprehensive review and compare the neutral zones for cities with different climates across the world. Neutral and preferred temperature values were found to be different also by the seasons [45,36,29,30,24,6,8,53,5,21]. There are also studies suggesting that the neutral temperature as represented in PET could be different from the preferred temperature [51,35,31]. These findings demonstrate the influence of the background climate on human, which lead to different degrees of thermal adaptation and seasonal acclimatization as well. Moreover, a study in Taiwan reported gender-related differences regarding the subjective assessment of the thermal environment, especially the sun-preference of subjects [49].

Systematic comparisons of subjective thermal evaluation among different geographical locations (and thus different climatic contexts) are still quite limited, especially accounting for the role of gender. This paper conducts a *meta*-analysis on the data of comprehensive OTC surveys and aims to reveal the common attributes and main differences regarding the subjective thermal perception and sun preference of Europeans for the time of year that is most suitable for outdoor activities, i.e., from April to October. More specifically, this paper will:

- determine the neutral temperature and thermal neutrality zone – expressed in *PET* – of the investigated cities;
- relate these outcomes to the climatic conditions of the study locations and to the small-scale meteorological characteristics of the investigations;
- evaluate the effect of gender on neutral temperature of different locations;
- compare the sun preference of male and female subjects of the investigated cities.

2. Database

2.1. Combined dataset

The RUROS (Rediscovering the Urban Realm and Open Spaces) database was used in this study. RUROS was funded by the EU 5th Framework Project, Key Action 4 "City of Tomorrow and Cultural Heritage" from the programme "Energy, Environment and Sustainable Development" and involved twelve different institutions from nine countries. It can be regarded as the most comprehensive OTC project to date. Nearly 10,000 of in-situ questionnaires were obtained by asking the users of characteristic open spaces in seven cities from five European countries. The questionnaires were supported with small-scale meteorological measurements [38]. Besides the RUROS project, this study uses the data of a later Hungarian project with substantial amount of questionnaires collected in Szeged [21]. Geographical information, population density and climatic information of these 8 cities are presented in Fig. 1 and Table 1.

Table 2 compares the two projects regarding their primary *meta*-data and the collected parameters. The questionnaires included items regarding the visitors' in-situ thermal sensation (TSV: thermal sensation vote), as well as their sun preference (SPV: sun preference vote). In the RUROS project, visitors could choose from five TSV categories while the Hungarians had nine options. We should emphasize that both TSV-scales ranged from 'very cold' to 'very hot', thus, it was easy to synchronize them: the categories were coded from −4 to + 4 as shown in Table 2. Concerning SPV, visitors had three options in the case of both projects. Although the RUROS scale can be interpreted as a transition between a preference and a perception scale, it was treated as a preference scale during the present analysis (similar to [29,30], and [21]).

It is worth emphasizing that a portion of the individuals who were interviewed in the RUROS project were not inhabitants of that city or even the country where the surveys were conducted. Therefore the earlier study outcomes do not fully represent how people in different cities have been acclimatized to the local climatic conditions, or reflect the geographical and possible cultural differences. For the purpose of the present study, only local inhabitants were included. Another selection criterion was the time when the survey was conducted. Only those interviewees surveyed during the warmer months, i.e., from April to October were kept, as these months are more suitable for outdoor activities in cities [21]. After this selection, each RUROS city is represented with 500–1000 subjects, the amount necessary for comprehensive statistical analysis. In the case of the long-term Hungarian project, 5414 subjects met the above-mentioned criteria. Table 3 summarizes the number of interviewed subjects included in the study. The filtered RUROS database has the most questionnaires collected in Fribourg and the least in Kassel. Fig. 2 shows the distribution of interviewees according to gender in the investigated cities. Generally speaking, a slightly higher proportion of male than female subjects was interviewed in each RUROS city, with the only exception being Athens, while for the case of the Hungarian project, a large majority of the interviewees were female.

It should be noted that there's inconsistency in the combined dataset due to lack of data: for the 7 cities in the RUROS project, data is not available for every month during the study period from April to October. For example, Thessaloniki doesn't have data from June to August which are summer months, and Cambridge doesn't have data for April, May, September and October, which are typical warm months. This inconsistency presents a formidable challenge to the comparability of data and the *meta*-analysis methods. Table 4 summaries months without data for the 7 RUROS cities and their respective climatic background as depicted in Fig. 1, and presents work-around methods employed in this study which use data available to reduce the impact of lack of data and ensure data comparability in the *meta*-analysis. For most cities, the lack of data for certain months can be represented by available data with similar climatic background. However, for Thessaloniki, no data from summer months is available, and for Cambridge, no data from warm months is available. This suggests that the results of the *meta*-analysis should be interpreted with caution especially for cities with substantial lack of data, and generalization regardless of data inconsistency should be avoided.

2.2. Urban human-meteorological data

The individuals' solar exposure – whether they stayed in the sun or in the shade – was noted by the interviewer. However, regardless of their actual solar exposure, values of unobstructed global radiation (G) from the nearest meteorological station was assigned to each subject. Besides, small-scale meteorological measurements were conducted to the subjects in parallel with the questionnaires. Air temperature (T_a), relative humidity (RH), wind speed (v) and the radiation conditions (T_{mrt}, mean radiant temperature) were recorded at 1.1 m above ground level or calculated from measured data. Detailed description of the instruments used in the RUROS and the Hungarian projects was given by Nikolopoulou & Lykoudis [38] and Kántor et al. [21], respectively. Both projects used mobile human-biometeorological stations equipped with sensors fulfilling ISO 7726 [18] comfort-survey requirements. The major difference between the projects concerns the radiation measurements and the calculation of T_{mrt}.

In the Hungarian project, T_{mrt} was calculated from the short- and long-wave radiation flux densities (K_i and L_i) measured from

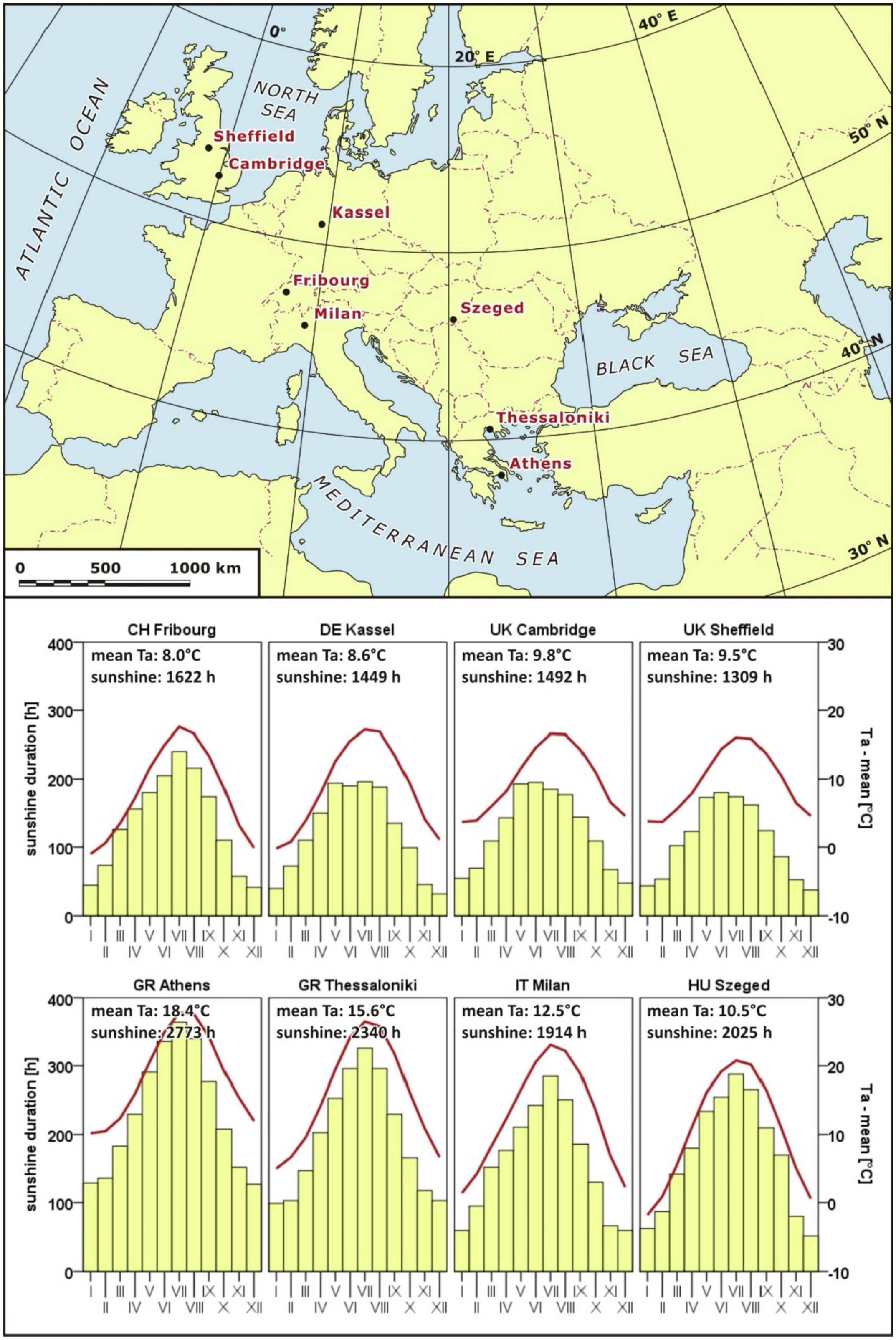

Fig. 1. Geographical location of the investigated European cities, and their climate diagrams (sunshine duration and mean temperature – T_a) based on Climatological Normal data (CLINO) for the period 1961–1990 (source of data: [52], Met Office, and Meteo Scheweiz).

six perpendicular direction of the environment (*i*: South, North, East, West, as well as the upper and lower hemisphere). The calculation was based on the equation proposed by Höppe [13].

In the RUROS cities researchers used a tailor-made globe thermometer: a grey-pained acrylic globe with 38 mm diameter [38]. This device was assumed to represent better the radiation charac-

Table 1
Descriptions of the investigated European cities. (source of data: local municipal websites).

City	Longitude	Latitude	Elevation (m)	Population (thousand, as of 2020)	Population density (/km^2, as of 2020)	Köppen climate classification
CH Fribourg	46°48′N	7°9′E	610	38	4100	Dfb
DE Kassel	51°18′N	9°28′E	167	201	1900	Cfb
GR Athens	37°59′N	23°43′E	194	664	7500	Csa
GR Thessaloniki	40°38′N	22°56′E	0	325	7423	Csa
IT Milan	45°28′N	9°11′E	120	1399	7700	Cfa
UK Cambridge	52°12′N	0°7′E	6	124	3120	Cfb
UK Sheffield	53°23′N	1°28′E	131	584	4100	Cfb
HU Szeged	46°15′N	20°8′E	76	160	612	Cfb

Table 2
Meta-data of the concerned OTC-projects (detailed explanations of the parameters can be found in the next paragraph).

	RUROS project	Hungarian project
Location	GR: Athens, ThessalonikiIT: Milan CH: Fribourg DE: Kassel UK: Cambridge, Sheffield	HU: Szeged
Year	2001, 2002	2011, 2012, 2015
TSV	(4) very hot (2) warm (0) neither cool nor warm (−2) cool (−4) very cold	(4) very hot (3) hot (2) warm (1) slightly warm (0) neutral (−1) slightly cool (−2) cool (−3) cold (−4) very cold
SPV	(1) prefer more sun (0) OK (−1) too much sun	(1) prefer more sunshine (0) want no change (−1) prefer less sunshine
Solar exposure	Stay in sun Stay in shade	Stay in sun Stay in shade
Meteorological station	*G* - global radiation	*G* - global radiation
In-situ measured parameters	T_a *RH* *v* $T_g \rightarrow T_{mrt}$	T_a *RH* *v* $K_i + L_i \rightarrow T_{mrt}$

teristics of the clothed human body and have better response time than the standard black-painted copper globes with 150 mm diameter [37,47,17]. The temperature measured inside the globe is called the globe temperature (T_g). T_g is influenced not only by radiation (T_{mrt}) but also by the convective heat exchange which depends on T_a and *v*. Thus, T_{mrt} can be calculated considering the measured T_g, T_a and v values [18]. For the purpose of this study, instead of using the original ISO-equation that has been adopted in the earlier RUROS-analyses [38], T_{mrt} was re-calculated according to the modified formula proposed by Thorsson et al. [47] as given in Eq. (1):

$$T_{mrt} = \sqrt[4]{(T_g + 273.15)^4 + \frac{1.335 \times 10^8 \times v^{0.71}}{\varepsilon \times D_g^{0.4}} \times (T_g - T_a)} - 273.15 \quad (1)$$

In Eq. (1) T_g, T_a and v are the measured globe temperature, air temperature and wind speed, respectively, ε is the globe's emissivity (0.95) and D_g is the globe's diameter (0.038 m). The main reason for adopting this formula and re-calculating the T_{mrt} values of RUROS cities was to enhance the comparability of the results. Thorsson et al. [47] derived this formula for small, grey-colored globe thermometers based on simultaneous radiation measurements including the six-directional technique (using net radiometers, just as in the Hungarian project) and a 38 mm diameter acrylic globe painted flat grey (just as in the RUROS project).

In order to parameterize the complex effect of the thermal factors (T_a, *RH*, v, T_{mrt}) on the human body, *PET* [15] was calculated. The calculation of *PET* is based on the energy balance model MEMI – Munich Energy-balance Model for Individuals [34,14]. In practice, *PET* and other human-biometeorological indices can be calculated easily with the RayMan software package (https://www.urbanclimate.net/rayman/), which has been commonly applied to urban human-biometeorology studies [33,27].

Admittedly the combined dataset built in such a way is not perfect: the interviews are not evenly distributed for each month for each city, and for some months there is a lack of data; and the measurement techniques of urban human-biometeorological parameters are different for RUROS and the Hungarian study. These drawbacks will induce obstacles on how the data could be interpreted. Nevertheless, this dataset is by far the most comprehensive OTC dataset for different European cities (with the least data of 494 questionnaires collected in Kassel) in diverse climatic zones (Csa, Cfa, Cfb and Dfb). The focus of the present study is the neutral temperature and neutral zone of these cities and the gender-related tendencies. Neutral temperature and neutral zone were derived via regression analysis (TSV vs. PET) in the case of all cities. Because of the central position of neutral votes on both TSV-scales and the same coding methods employed (from −4 to + 4, with 0 indicating neutral / neither cool nor warm votes), as well as the large sample in the case of all cities, it is believed that the data analyses results are comparable and can reveal informative patterns and tenden-

Table 3
Number of subjects who were included in the analysis of the present paper.

Project	City	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
RUROS	CH Fribourg	325	72	212	72	0	62	264	1007
	DE Kassel	0	138	0	0	232	0	124	494
	GR Athens	171	82	0	94	274	0	0	621
	GR Thessaloniki	186	50	0	0	0	549	0	785
	IT Milan	0	254	0	290	0	0	136	680
	UK Cambridge	0	0	326	243	86	0	0	655
	UK Sheffield	207	0	0	0	190	0	135	532
HUNGARY	HU Szeged	1202	1198	453	395	250	916	1001	5415

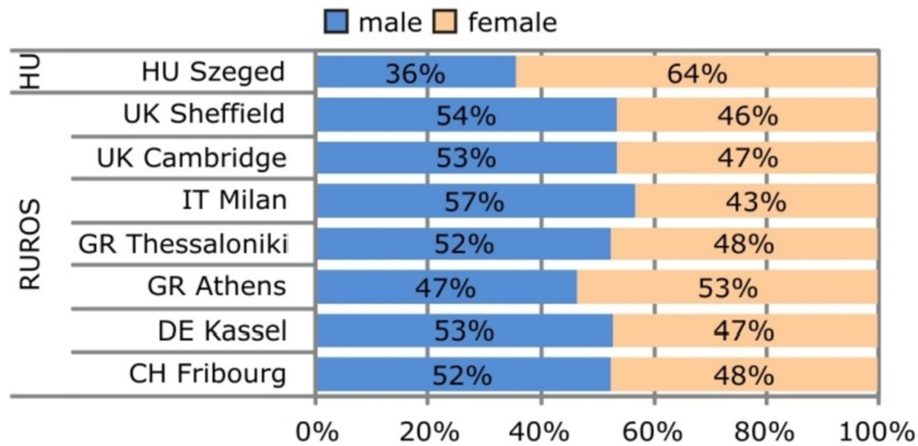

Fig. 2. Distribution of interviewees according to gender in the investigated cities.

Table 4
A summary of the lack of data for certain months for the 7 RUROS cities with their climatic information as represented by mean air temperature T_a (°C) and sunshine duration S (h), and work around methods employed to ensure data comparability.

City	Month without data and its climatic information (T_a, S)	Work-around
CH Fribourg	Aug (16.1 °C, 219 h)	Jul (18.0 °C, 242 h) and Jun (15.4 °C, 206 h) are used to represent summer months.
DE Kassel	Apr (8.1 °C, 152 h) / Sep (14.0 °C, 139 h)	Oct (9.5 °C, 101 h) is used to represent warm months.
	Jun (15.8 °C, 193 h) / Jul (17.5 °C, 199 h)	Aug (17.1 °C, 190 h) is used to represent summer months.
GR Athens	Jun (25.2 °C, 337 h)	Jul (28.0 °C, 362 h) and Aug (27.2 °C, 341 h) are used to represent summer months.
	Sep (24.1 °C, 278 h) / Oct (18.0 °C, 205 h)	Apr (16.0 °C, 228 h) and May (20.0 °C, 288 h) are used to represent warm months.
GR Thessaloniki	Jun (24.2 °C, 292 h) / Jul (26.4 °C, 323 h) / Aug(25.8 °C, 291 h)	None for summer months, i.e., no summer data.
	Oct (15.8 °C, 162 h)	Apr (14.1 °C, 201 h) is used to represent warm months.
IT Milan	Apr (12.0 °C, 178 h) / Sep (18.2 °C, 182 h)	May (16.3 °C, 209 h) and Oct (12.2 °C, 130 h) is used to represent warm months.
	Jun (20.0 °C, 241 h) / Aug (21.7 °C, 248 h)	Jul (22.8 °C, 282 1) is used to represent summer months.
UK Cambridge	Apr (8.1 °C, 142 h) / May (12.0 °C, 197 h) / Sep (14.2 °C, 142 h) / Oct (10.1 °C, 111 h)	None for warm months, i.e., no warm season data.
UK Sheffield	May (10.8 °C, 176 h) / Sep (14.2 °C, 121 h)	Apr (7.8 °C, 122 h) and Oct (10.2 °C, 92 h) are used to represent warm months.
	Jun (14.1 °C, 182 h) / Jul (16.1 °C, 177 h)	Aug (16.0 °C, 163 h) is used to represent summer months.

cies in such a context. The readers are also referred to Section 5.1 on the discussions of difference found, limitations and influences of different T_{mrt} determination methods.

3. Data analyses methods

The RUROS database formed solid basis for previous OTC studies (e.g., [38–39]) but with a focus different from the current study. Earlier analysis calculated neutral temperature based on the air temperature (T_a), which is predominantly used by urban designers. The present study instead focuses on *PET* which is widely used in the field of human- biometeorology and has been gradually adopted by planning authorities in some parts of the world.

Previous RUROS analyses [38] determined the neutral temperature and the corresponding neutrality zone according to the probit technique [2]. These measures can be obtained according to another popular technique, when TSV is potted against the objective index (*PET*), and regression analysis is used (e.g., [29,30,6,54,5,55,21]). Because in the RUROS project less TSV categories were used than in Hungary, the probit analysis might lead to wider neutral zones in RUROS cities than in Szeged where nine TSV categories were used. To avoid the discrepancy in data interpretation, this study adopts regression analysis for the allocation of neutral temperature and neutral zone, since this technique is less sensitive to the number of applied TSV categories.

Besides the examination of thermal perception patterns (*PET*-TSV), Kendall's and Spearman's rank correlation coefficients were used to compare sun preference patterns among different European populations: Kendall's rank correlation coefficient (*tau-b*) was used to reveal the association between the subjective thermal sensation and sun preference (TSV-SPV), and of Spearman's rank correlation coefficient (*rho*) was used to examine the influence of solar radiation on the subjects' sun preference (*G*-SPV). The two methods were used because Kendall's coefficient measures the strength of dependence between two ordinal variables (in this case: SPV and TSV are both ordinal data), and Spearman's coefficient measures the degree of association between two variables which are at least ordinal (in this case: SPV is ordinal and G is the scale variable). All of these parameters are calculated for each city and for different population subgroups to allow a detailed gender (male/female) analysis.

4. Results

4.1. Urban human-meteorological assessment

Fig. 3 shows the thermal conditions including T_a and *PET* during the interviews from April to October for the investigated cities during the survey campaigns. Considering the microscale human-biometeorological background of the RUROS interviews, the widest T_a and *PET* range can be observed in Fribourg. The lowest mean and median T_a occurred in Fribourg and Sheffield, while the highest in Athens and Thessaloniki, followed by Milan and Cambridge. Compared to the climatic background of the locations, thermal conditions during the interviews were quite warm in the case of the Central and Northern European cities: for the cities of Cambridge, Sheffield, Fribourg and Kassel, the mean T_a during the interviews were 23.0 °C, 16.7 °C, 16.7 °C, and 20.5 °C, respectively. Although

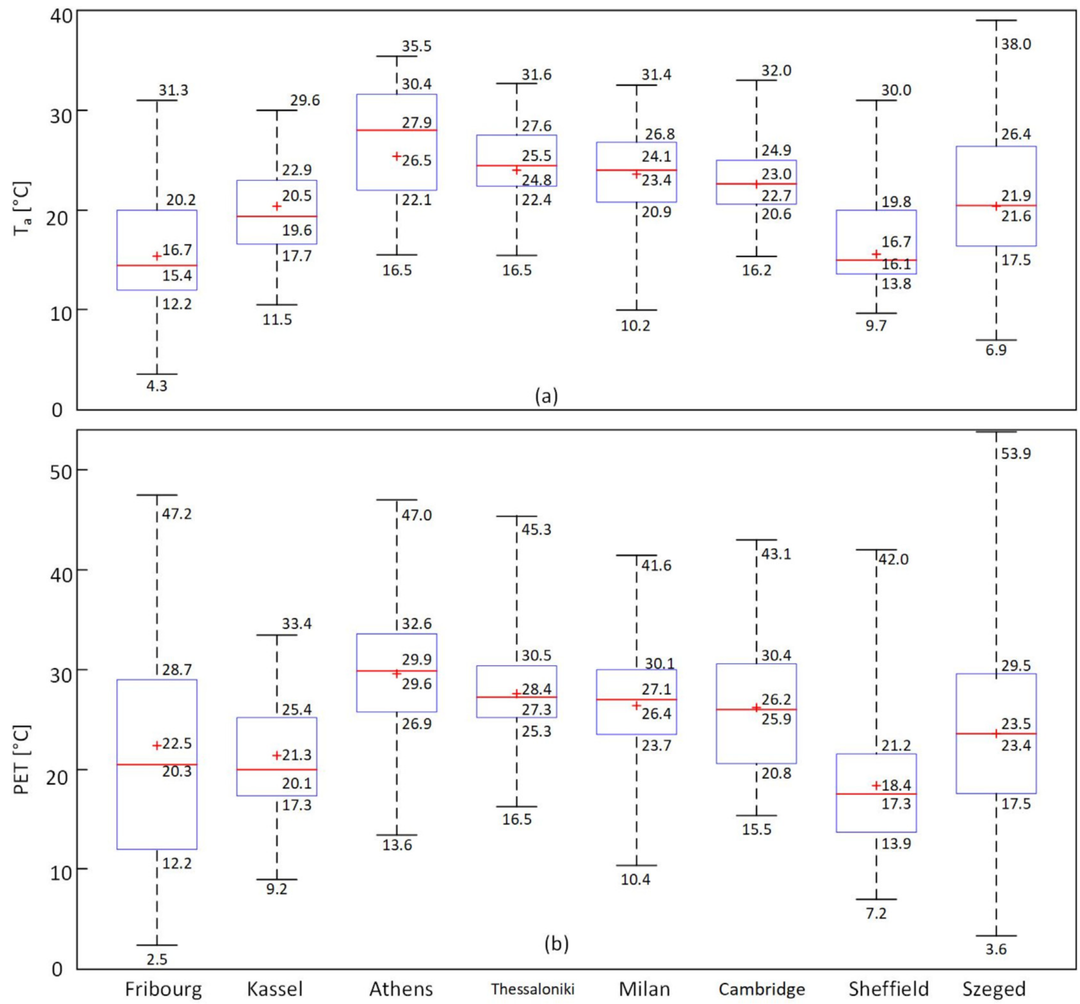

Fig. 3. Thermal conditions during the interviews conducted from April to October: (a) T_a; (b) PET. Black solid line: Min and Max value; blue solid line: lower and upper quartile; red solid line: median; red "+": Mean value.

the highest maximum *PET* was obtained in Fribourg, the median and the third quartile values were higher in the South European cities (Thessaloniki, Athens and Milan). In spite of the lack of the hot months (June, July and August) in Thessaloniki's database, interviewees of Thessaloniki expected obviously the second warmest thermal conditions after Athens. Mean *PET* was higher than mean T_a in every city; besides, minimum values were lower and maximum values were higher in the case of *PET*. It is worth mentioning that the lowest maximum T_a and maximum *PET* occurred in Kassel; the city's maximum *PET* (33.4 °C) was 8 to 14 °C cooler than in other cities.

The lowest Hungarian T_a (6.9 °C) was close to Fribourg's 4.3 °C while the maximal value (38 °C) exceeded even the warmest RUROS city of Athens (35.5 °C). The wider Hungarian T_a-range can be explained with the great number of measurements covering wider spectrum of thermal conditions. The mean and minimum *PET* values in Hungary (23.5 °C and 3.6 °C) was similar as in Fribourg (22.5 °C and 2.5 °C), but the maximum *PET* in Szeged (53.9 °C) exceeded the highest RUROS value (calculated also for Fribourg: 47.2 °C). Again, the wide *PET* range in Szeged can be explained with the huge number of measurement days in Hungary.

Fig. 4 shows the solar radiation background from April to October for the investigated cities during the survey campaigns. The pattern was quite similar in all RUROS cities. This is especially true for the mean *G* values: the lowest occurred in Milan (420 W/m^2) while the highest in Thessaloniki (493 W/m^2). It should be noted that since Thessaloniki doesn't have data from June to August (Table 4), the actual *G* value during the study period is expected to be even higher. The median *G* was considerably greater than the mean value in Thessaloniki and Athens, suggesting that the selected radiation values flow a left-skewed distribution, i.e., with more values smaller than the mean. Also, zero *G* values were found in the two Greek cities and Milan, which is because the measurements in these locations were conducted until 8–9 pm, that is, after sunset as this time corresponds usually to the highest attendance on Mediterranean urban public spaces. The greatest maximum *G* was measured in Kassel and the widest inter quartile range (IQR, defined as IQR = Q3–Q1) occurred in Athens. The mean global radiation of Szeged (513 W/m^2) exceeded the corresponding values of the RUROS cities, and the middle 50% of the Hungarian *G* data fell between 332 and 700 W/m^2, resulting in the narrowest IQR among all locations. This is largely due to the strict and consistent measurement protocol in Hungary: the measurements lasted from 10 am to 6 pm on each survey day. Fig. 5 summarizes the percentage of interviews conducted at each time period of day and the corresponding mean solar radiation values for the 8 cities.

4.2. Subjective assessment regarding the thermal conditions and sunshine

Fig. 6 presents the proportional distributions of the different TSV and SPV categories in the investigated cities. In the case of

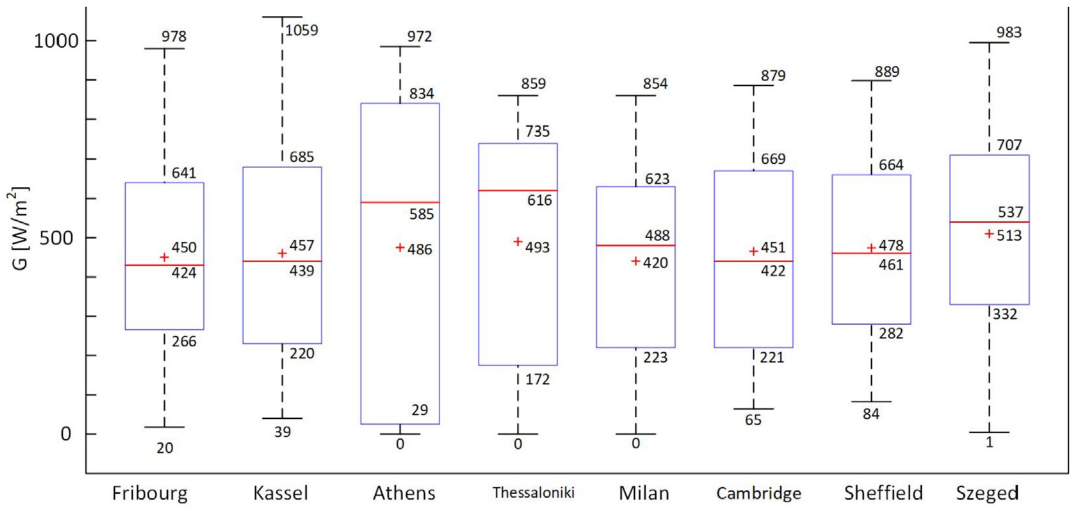

Fig. 4. Unobstructed global radiation values from the nearest meteorological station during the time of the interviews conducted from April to October. Black solid line: Min and Max value; blue solid line: lower and upper quartile; red solid line: median; red "+": Mean value.

the RUROS project, the most homogeneous TSV frequency distribution was found in Milan and Kassel where people felt most often 'neutral'. Around 40% felt at least warm in Fribourg and Sheffield, while almost 70% of the subjects selected these categories in Cambridge, which is as expected since Cambridge doesn't have data for months with lower T_a (Table 4). The highest proportion of cool votes was recorded in Thessaloniki, followed by Athens and Sheffield. The existence of the few 'very cold' votes may be explained on the one hand with month April, when the weather is sometimes chilly in the cooler climate cities (Sheffield, Fribourg). On the other hand, the RUROS TSV scale let the subjects to select only from 5 options, without 'cold' category. It could be speculated that a 7-point TSV scale with more answer options (e.g. [48,29,5]) would presumably have encouraged subjects to select 'cold' category instead of 'very cold' or 'cool'. Indeed, during the Hungarian project visitors could select from nine main categories which resulted in a more diverse TSV distribution. In Szeged ca. 39% of the subjects felt neutral or cooler and out of the remaining 61% of votes, 29% reported slightly warm and 25% warm thermal sensation.

Regarding the RUROS subjects' sun preference, the most balanced distribution occurred in Milan, with a huge proportion of 'OK' (want no change) SPV votes and nearly equal portion of 'prefer more sunshine' and 'prefer less sunshine' answers. Besides Milan, 'OK' votes dominated in Cambridge, Thessaloniki, Athens and Fribourg. The first two cities should be examined more carefully due to the data inconsistency issue (Table 4). For Cambridge, the 64% 'OK' vote is likely to underestimate subjects' actual sun preference since the 4 months without data (April, May, September and October) normally had adequate but not excessive sunshine. Likewise, the 76% 'OK' vote for Thessaloniki is likely to overestimate subjects' actual sun preference due to the lack of data for all summer months (June to August) when sunshine was normally excessive. Sheffield and Kassel interviewees demonstrated a prominent sun preference. However, the 61% 'prefer more' vote for Sheffield is likely to overestimate the sun preference since the 3 months without data (May to July) had the highest sunshine duration. The proportions of 'prefer more' votes also exceeded 30% in Fribourg and Cambridge. The greatest percent of 'prefer less' votes (in fact, 'too much sun') were recorded in Athens, Thessaloniki and Milan which were actually the hottest cities regarding the interviews' mean and median *PET* values. Similar to the 'prefer more' proportion in Fribourg and to the 'prefer less' proportion in Milan, 37% of the Hungarian subjects wished for stronger sunshine and 15% of them wanted weaker solar radiation.

The connection between the interviewees' TSV and SPV also shows noticeable features, as shown in Fig. 7(a). It should be noted that nobody selected 'very cold' TSV in Athens and Milan, and generally, the number of 'very cold' votes was quite low in all cities during the investigated months. Therefore, the SPV-percentage distribution may seem distorted for this TSV category. In Thessaloniki, Kassel, Athens and Milan the 'prefer less' sun votes dominated when TSV was 'very hot', however, for the same TSV, the 'OK' sun votes were the most frequent in Fribourg, Cambridge and Sheffield. This is in agreement with findings for psychological adaptation, where there is preference for cooler conditions in hotter climates and warmer seasons [45,40]. It is worth mentioning that overwhelming proportion of the people in the Greek cities did not want more sunshine even in the case when their TSV was cooler than neutral.

Using Kendall's *tau-b* as a measure for the connection strength between TSV and SPV, significant (0.000) correlations were revealed in the case of all cities (Table 5). Both the negative *tau-b* values and the charts on Fig. 7(a) indicate that people generally prefer more sunshine when they feel cooler than neutral and they want decreasing solar radiation when they feel warmer than neutral. Among the RUROS cities the strongest correlation (*tau-b* close to or below −0.35) were found in Milan, Sheffield, Thessaloniki and Fribourg. Offering more TSV options and having greater number of subjects in Szeged, the TSV-SPV connection was even stronger. Regarding the gender differences, the correlation between the two subjective assessments was always stronger for female subjects, except in Thessaloniki, suggesting that women's sun preference depends more on their actual thermal sensation.

The dependence of the interviewees' sun preference on the actual value of global radiation was also investigated. Percentage distribution of SPV categories was illustrated according to 100 W/m^2-wide global radiation intervals, as shown in Fig. 7(b). 'Prefer more' sunshine vote dominated in the case of almost all *G* categories in Kassel and Sheffield, while 'OK' sun votes were the most common choice in Thessaloniki, Athens, Milan, as well as in Cambridge and Fribourg. Athens and Thessaloniki can be characterized with the highest proportion of 'prefer less' sunshine votes, especially in the case of *G* above 600 W/m^2. Climatologically, these cities are the warmest and these can be characterized with the strongest solar radiation, especially during the summer months.

The strongest connection between SPV and *G* was found in Szeged, followed by Sheffield, Thessaloniki and Fribourg (Table 6). In five cities out of the eight, the subjective sunshine assessment of

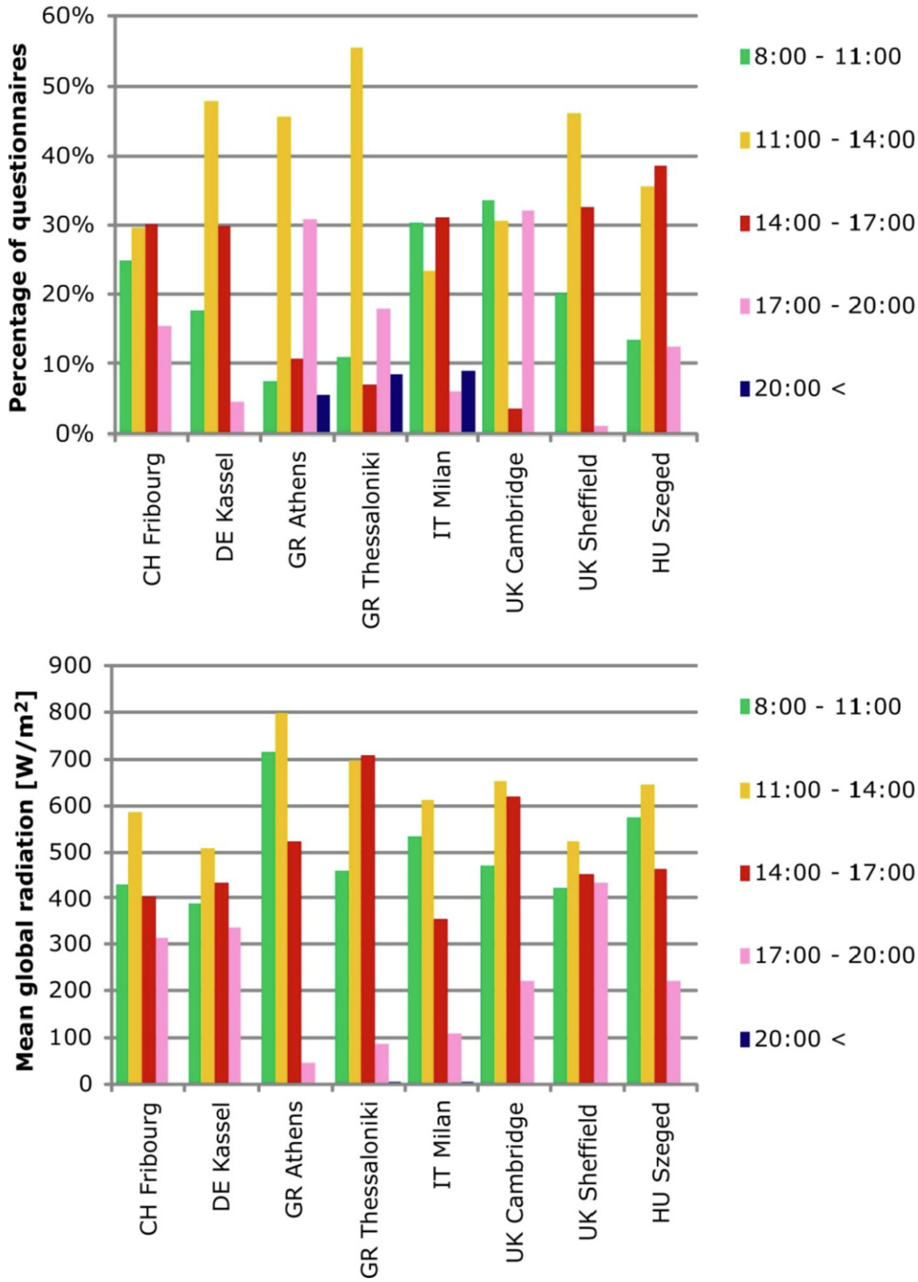

Fig. 5. Percentage of interviews and the mean solar radiation during different time periods.

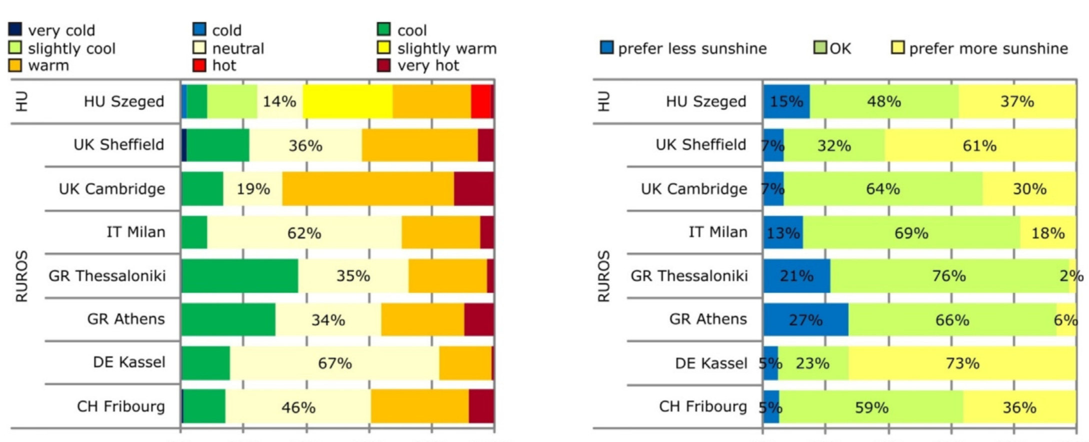

Fig. 6. Thermal sensation and solar preference votes in the investigated cities.

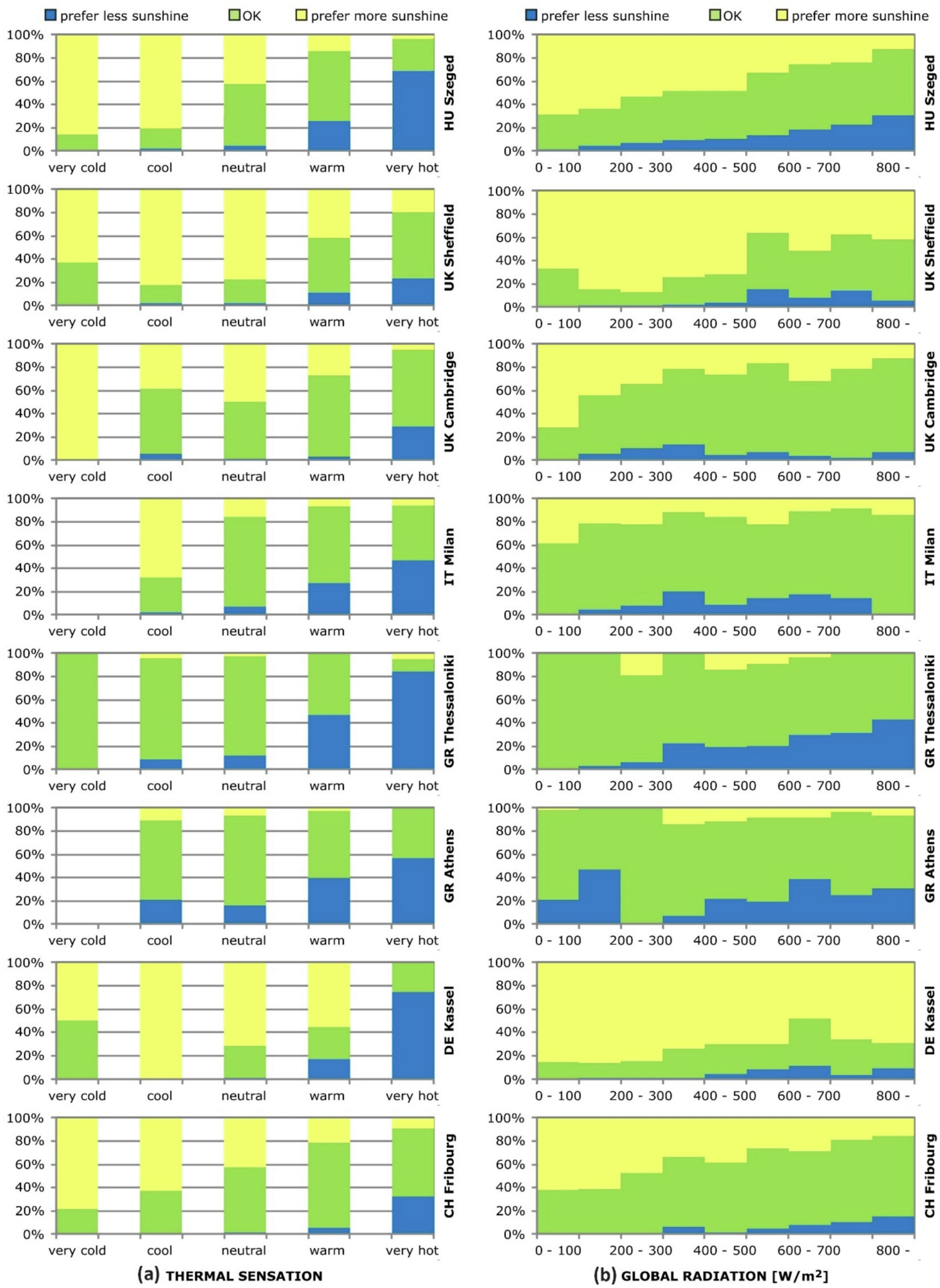

Fig. 7. Percentage distribution of visitors' SPV according to (a) their TSV categories and (b) global radiation.

females reflected more sensitively the changes in *G* than that of males. In the case of Sheffield and Szeged however, the correlation was stronger in male interviewees, and in the case of Athens the SPV-*G* connection was not significant at all.

4.3. Neutral temperature and neutral zone

In this paper we selected simple regression technique between *PET* and TSV for the determination of neutral temperature (Fig. 8, Table 7). The reason for using the original TSV values instead of averaging them according to 1 °C-wide *PET* bins (like for example in [29] is that we intended to demonstrate the great variety of subjective assessments in spite of the same thermal conditions, as well as point out those thermal conditions where certain TSV votes accumulated in the different study locations.

Indeed, Fig. 8 reveals substantial dominance of zero TSV votes in Milan, Kassel and Fribourg; however, the main accumulation zone is different in the mentioned cities: 22–29 °C in Milan, 16–20 °C in Kassel, and the lowest and widest in the case of Fribourg: 11–22 °C. Although 'neutral' votes were frequently selected in Thessaloniki

Table 5
Correlation (Kendall's tau-b) between the visitors SPV and TSV votes.

City	All data			Males			Females		
	Tau-b	Sig	N	*Tau-b*	Sig	N	*Tau-b*	Sig	N
CH Fribourg	−0.347	0.000	961	−0.342	0.000	495	−0.355	0.000	456
DE Kassel	−0.302	0.000	494	−0.286	0.000	259	−0.330	0.000	234
GR Athens	−0.223	0.000	469	−0.184	0.002	227	−0.263	0.000	242
GR Thessaloniki	−0.350	0.000	785	−0.394	0.000	412	−0.302	0.000	373
IT Milan	−0.389	0.000	538	−0.349	0.000	286	−0.434	0.000	252
UK Cambridge	−0.284	0.000	655	−0.213	0.000	350	−0.370	0.000	305
UK Sheffield	−0.365	0.000	500	−0.365	0.000	259	−0.366	0.000	241
HU Szeged	−0.465	0.000	5390	−0.440	0.000	1913	−0.481	0.000	3472

Table 6
Correlation (Spearman's rho) between the visitors SPV and the G values (*Italics* indicate not significant correlations at 0.05 levels).

City	All data			Males			Females		
	Rho	Sig	N	Rho	Sig	N	Rho	Sig	N
CH Fribourg	−0.302	0.000	960	−0.281	0.000	495	−0.338	0.000	455
DE Kassel	−0.207	0.000	487	−0.184	0.003	255	−0.237	0.000	231
GR Athens	*−0.056*	*0.225*	*469*	*−0.069*	*0.298*	*227*	*−0.049*	*0.445*	*242*
GR Thessaloniki	−0.306	0.000	736	−0.299	0.000	383	−0.313	0.000	353
IT Milan	−0.130	0.003	515	*−0.083*	*0.169*	*273*	−0.182	0.004	242
UK Cambridge	−0.183	0.000	655	−0.138	0.010	350	−0.246	0.000	305
UK Sheffield	−0.350	0.000	500	−0.414	0.000	259	−0.281	0.000	241
HU Szeged	−0.356	0.000	5326	−0.365	0.000	1889	−0.352	0.000	3432

too (especially in the 26–29 °C *PET* range), the subjects of this city choose predominantly the 'cool' category (−2) between 23 and 28 °C. This may be the effect of psychological thermal adaptation: in Thessaloniki, summer surveys were conducted during September, after the really hot summer months, and local people may find these conditions cooler by comparison to the earlier summer conditions. In the case of Cambridge, 'warm' (2) votes were picked most frequently and these votes accumulated in a relatively wide *PET* domain: 24–33 °C. The most common thermal sensation categories were 'slightly warm' (1) and 'warm' in Hungary.

The *PET*-TSV regression was significant in the case of all cities (Table 7). The lowest R^2 value was found in Thessaloniki while the highest in Szeged and Fribourg where the field survey days covered most evenly the investigation period; this is reflected also in the wide distribution of *PET* and TSV values. The R^2 values were almost the same in the case of quadratic regression than in the case of the linear model except Szeged and Cambridge where quadratic regression seems a better fit. Neutral temperature (*nPET*) and the neutral *PET* zone were calculated by substituting 0, −0.5 and 0.5 TSV values into the obtained regression equations. The greatest *nPET* difference – between the regression models – was found in the case of Cambridge (1.7 °C), while the *nPET* values of different regression were the same in Sheffield, and almost the same in Fribourg, Milan and Thessaloniki. We found the lowest *nPET* in Sheffield, followed closely by Fribourg and Cambridge, while the highest *nPET* in Thessaloniki, followed by Athens. The neutral temperature of Szeged was close to the *nPET* values of Cambridge and Fribourg. Although the *nPET* values obtained via quadratic and linear regression fell quite close to each other, slightly greater differences were found between the width of the quadratic and linear neutral zones. Kassel and Thessaloniki has the widest neutral zone, suggesting that these populations were not too sensitive against the changes of the thermal environment. The narrowest zones were found in Cambridge and Sheffield.

The forthcoming gender analysis relies on linear model only; except for Cambridge and Szeged where quadratic regression was used because of the higher R^2 values. Fig. 9 demonstrates that female subjects felt generally neutral at higher *PET* values, that is, at warmer thermal conditions. This is especially true for the lower boundary of the neutral *PET* zone. The greatest *nPET* differences between men and women were found in Milan (2.9 °C) and Kassel (2.6 °C), while the smallest in Sheffield (0.4 °C). The upper boundary of the neutral zone for males and females were almost the same in Thessaloniki, Sheffield and Szeged. The width of the neutral zone was generally wider in the case of male subjects, revealing that women are more sensitive to the changes of the thermal environment. The two exceptions are Kassel and Cambridge, where the neutral zones were broader in the female group, with 0.5 °C and 0.3 °C, respectively.

5. Discussion

5.1. Discussion of the obtained differences found among cities

In most cities, the greatest part of visitors wished for more sunshine when they felt neutral or cooler as well as when the global radiation was weak, and increasing proportion of subjects assessed sunshine too much with rising TSV and stronger global radiation (Fig. 7). However, most subjects in Thessaloniki and Athens did not want more sunshine even in the case when their thermal sensation was cooler than neutral. One reason is that a considerable amount of the questionnaires in these cities were done in the evening and after sunset, when the highest number of people was found outdoors [39]. Indeed, Fig. 5 reveals that a huge number of interviews were conducted after 19:00 in the Greek cities, as well as in Milan, when the mean solar radiation was zero, or it was close to zero.

Regarding the interviewees' neutral temperature, Fribourg and Cambridge, as well as Kassel and Milan seem to be very close to each other, and the lowest and highest *nPET* values were obtained for Sheffield and Thessaloniki, respectively (Table 7). Although the monitored thermal conditions were not too diverse in Kassel and Thessaloniki (these cities had the narrowest *PET* range and IQR, respectively, Fig. 3) the widest neutral *PET* zone was found in these locations (Table 7, Fig. 9). On the other hand, the narrowest neutral zones were obtained for Cambridge and Sheffield, that is, for those cities which can be characterized with the smallest temperature amplitude throughout the year (Fig. 1). Since the research focus

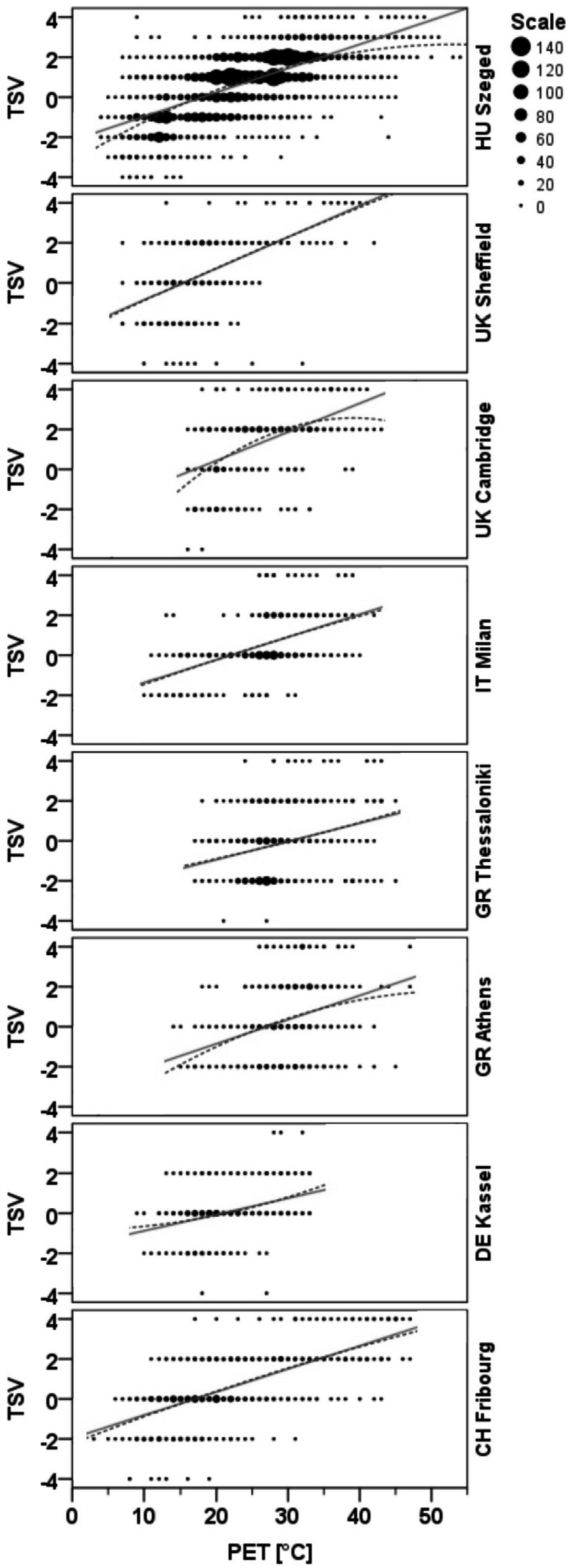

Fig. 8. Quadratic and linear regression between TSV and PET (using 1 °C wide PET bins).

was on the fully acclimatized population, this argument – the wider the temperature variation, the wider the comfort zone of the local population – supports thermal adaptation theory.

In order to reveal whether background climate or immediate micrometeorological conditions have greater impact on the obtained neutral temperatures, Pearson correlation coefficient (R) was calculated between *nPET* and selected temperature parameters. At micrometeorological level, mean and median air temperature values of the interviews were considered, and at climatological level, weighted mean and maximum temperature values ($Tmean^*$ and $Tmax^*$) were used. The latter two were calculated based on the climate normal data (1961–1990) of every city and the number of questioned individuals per month:

$$Tmean^* = \sum_{i=Apr}^{Oct} w_i \times Tmean_i \quad (2)$$

$$Tmax^* = \sum_{i=Apr}^{Oct} w_i \times Tmax_i \quad (3)$$

where i means the analyzed months from April to October, $Tmean_i$ and $Tmax_i$ are the average temperature and average maximum temperature of month i, and w_i is a weighting factor depending on the number of individuals (N_i) questioned in month i:

$$w_i = N_i / \sum_{i=Apr}^{Oct} N_i \quad (4)$$

Pearson's R was similar between *nPET* and all of the mentioned temperature parameters: being slightly smaller for the micrometeorological conditions (0.81 for *mean* T_a and 0.82 for *median* T_a) than for the weighted climatological background temperatures (0.85 for $Tmax^*$ a 0.86 for $Tmean^*$). However, a graphical illustration of these parameters reveals that the neutral *PET* temperature was greater in every city than $Tmean^*$ (Fig. 10). This can be explained by the time of the interviews (from 8 am to evening) which corresponds better to the period of the daily maximum temperature.

Neutral *PET* was very close to $Tmax^*$ in Sheffield, Fribourg and Athens. The difference between them was smaller than 3 °C in Milan and Kassel, while in Thessaloniki *nPET* was 5 °C higher than $Tmax^*$ (and *mean* T_a). Although climatologically Athens is the hottest among the investigated cities, the inhabitants of Thessaloniki had the highest neutral temperature suggesting very pronounced adaptation to heat. The high *nPET* may be related to the time of the interviews: in Thessaloniki, greater proportion of surveys was conducted in the hottest time of the day, that is, between 11 am and 2 pm (Fig. 5). On the other hand, June, July and August months are missing from the database of Thessaloniki and the majority of questionnaires were conducted there in September (Table 3). Being accustomed to the summer heat for this time, the population of Thessaloniki might perceive warmer thermal conditions as neutral (resulting in higher *nPET).*

In the end of this section we should note that although we sought to ensure the comparability of the results, the comparison of *nPET* between Szeged and the other cities should be interpreted carefully. This is because *PET* depends greatly on T_{mrt}, and different radiation measurement techniques were used during the Hungarian and the RUROS projects. Regrettably there are very few studies those compared and validated grey globe thermometer-based T_{mrt} values (or any other techniques) with those based on the most accurate, six-directional technique. Thorsson et al. [47] found that the grey globe technique (applying a grey painted table tennis ball) was accurate, especially when using 5 min averages instead of 1-minute values, and suggested it as a much cheaper and more mobile alternative instead of the expensive and robust six-directional measurements with net radiometers. They also found

Table 7
TSV-*PET* regression models (TSV = b1 × *PET* + const) as well as the resulted neutral temperatures values and neutral zones for the 8 cities, as ordered by their climatic zones.

	Climatic Zone	Regression model						
		R^2	sig.	const.	b1	*nPET*	neutral zone	
GR Athens	Csa	0.100	0.000	−3.269	0.121	27.1	22.9	31.2
GR Thessaloniki	Csa	0.079	0.000	−2.755	0.091	30.2	24.7	35.7
IT Milan	Cfa	0.259	0.000	−2.508	0.114	22.0	17.6	26.4
DE Kassel	Cfb	0.127	0.000	−1.695	0.082	20.8	14.6	26.9
UK Cambridge	Cfb	0.247	0.000	−2.427	0.143	16.9	13.5	20.4
UK Sheffield	Cfb	0.310	0.000	−2.421	0.157	15.4	12.2	18.6
HU Szeged	Cfb	0.471	0.000	−2.167	0.120	18.0	13.9	22.2
CH Fribourg	Dfb	0.441	0.000	−1.960	0.115	17.0	12.6	21.3

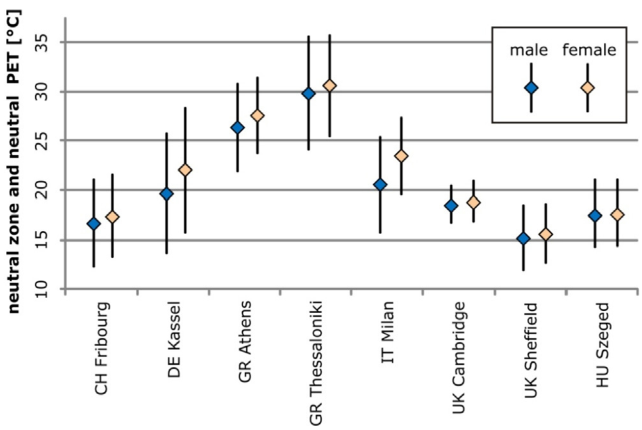

Fig. 9. Neutral zone and neutral temperature (*nPET*) according to gender.

in the Swedish study that the grey globe technique slightly overestimated T_{mrt} during shady conditions and slightly underestimated it during sunny conditions. However, a most recent study from Hong Kong [50] found that the widely used 40 mm acrylic globe thermometer significantly underestimates T_{mrt}, especially in clear weather conditions.

There is a pronounced lack of studies with complex human-biometeorological measurements in urban environments including different radiation measurement techniques – and involving different urban structures and weather conditions – with the aim of expressing the effect of T_{mrt} technique differences in terms of *PET* or other thermal indices. Until the publication of such a comprehensive study, we shall interpret and compare our *nPET* results (and any other OTC survey-based neutral index-temperatures and newly determined 'thermal comfort zones') with caution, and focus more on the discovered tendencies than on the absolute values.

5.2. Discussion of the obtained gender differences

Regarding the gender differences, females' *nPET* was always greater, indicating that European women feel neutral under slightly warmer thermal conditions than men; this aplies more for the lower and less for the upper thresholds of the neutral zone (Fig. 9). According to indoor thermophysiological studies men and women prefer almost the same thermal environment. Women's skin temperature and evaporation loss are slightly lower than those for men, and this balances the slightly lower metabolic rate of women [44].

In this context, it is worth comparing the findings from the current study with the gender-related outcomes of an OTC study from the Far East. Tung et al. [49] found 0.9 °C *nPET* difference in Taiwan, however, in that case the male subjects had the higher value: 26.1 °C compared to the women's 25.2 °C. The authors discussed that Taiwanese females are less tolerant to hot conditions, and they

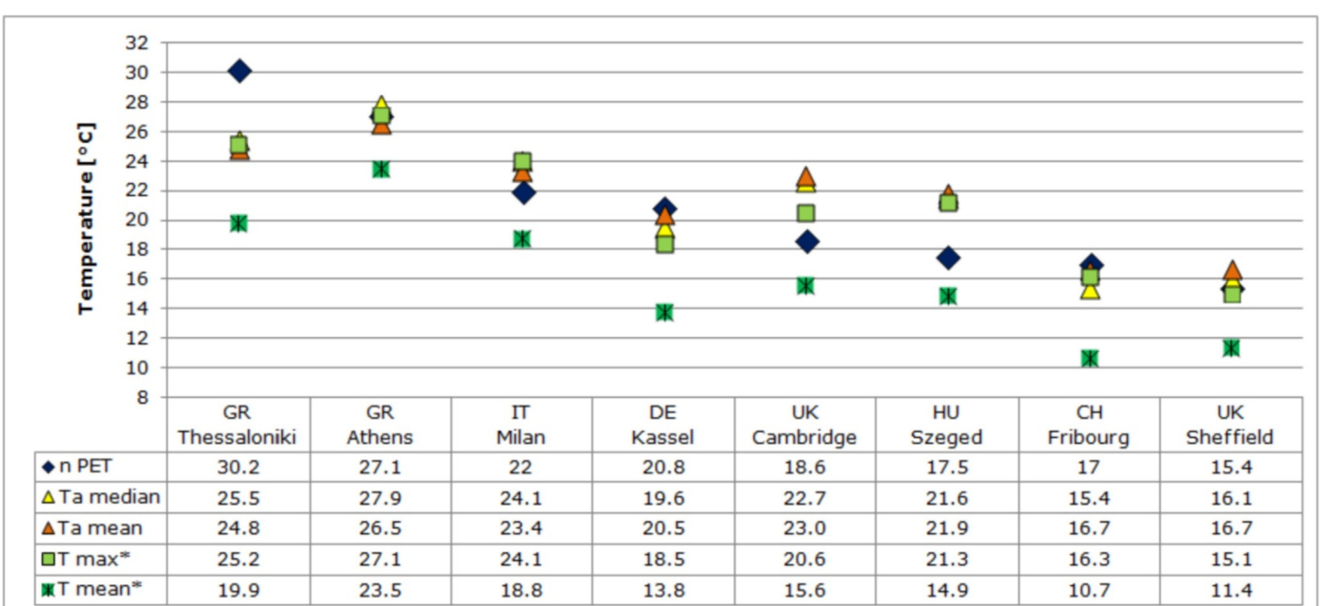

Fig. 10. Neutral *PET* values compared with meteorological parameters (Max, Min, Mean and Median of T_a). The parameters shown were based on the meteorological data obtained during the interviews.

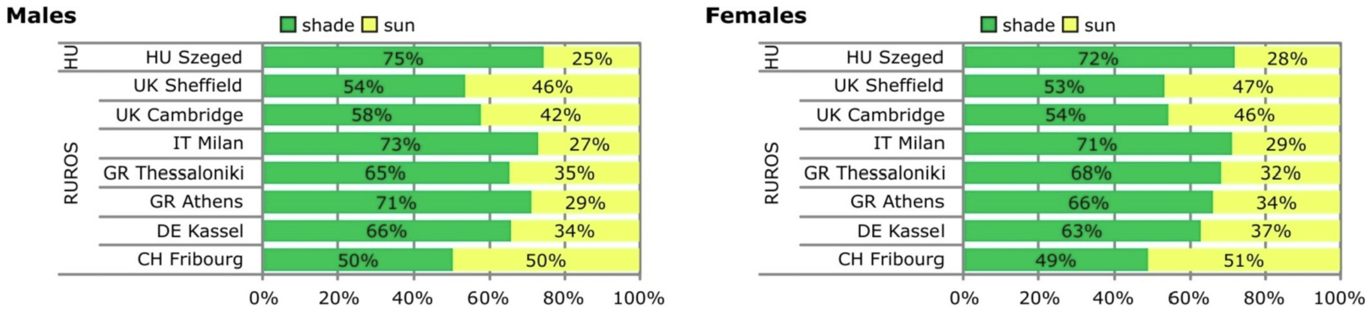

Fig. 11. Proportion of different sun-exposure groups according to gender and city.

intensely protect themeselves against the sunshine with umbrellas, looking for shaded places to stay. The slope value of the TSV-*PET* regression function of males and females was almost the same in Taiwan, resulting in the same width of neutral zone. The contrary applies in the current study; women's neutral *PET* zone was found to be slightly narrower (Fig. 9), while, in the case of almost every European city, the SPV-TSV and SPV-*G* connections were stronger in the female group (Tables 5 and 6). This suggests that women are more sensitive to the changes of environmental conditions. This is in agreement with findings from the indoor ASHRAE database of field surveys, where women appear to be more sensitive to changes in temperature, with the rate of change of thermal sensation with temperature for men being 75% that of women [7].

Compared to the Taiwanese female subjects who protect their skin against suntan with clothing and different accessories (sunhats, gloves and long extra sleeves made from light clothing), European women generally prefer to expose themeselves more to the sunshine than males (Fig. 11), adapting relatively easily to the changes of the thermal conditions (provided if it is not extreme thernal stress) by removing or adding clothing pieces. However, the overwhelming portion of interviewees in the shade draws attention on the importance of appropriate shading (by trees and artificial shading facilities) in outdoor urban spaces, especially in summertime conditions [26,28,46].

6. Conclusions

Aiming at the detection of differences regarding subjective assessments of the outdoor thermal environment and sunshine in different geographical locations and genders, *meta*-analyses were conducted using comprehensive European outdoor thermal comfort surveys. The analyzed databases originated from Szeged (Hungary) and seven other European cities (included in the RUROS project). The datasets were filtered for local residents to truly reflect the subjective thermal perception-patterns of people who are acclimatized to the local climate conditions, and for the months of typical outdoor urban activities in European cities (i.e., from April to October).

The following main study outcomes support thermal adaptation theory:

- Neutral temperature (*nPET*) of people shows strong correlation both to their immediate small-scale thermal conditions and to the long-term climatic background temperatures of their cities (Pearson's R was found to be above 0.8 between *nPET* and the selected temperature indices). Besides, *nPET* is closer to the weighted maximum temperature of the investigated months (*Tmax**) than its weighted mean temperature.
- Neutral zone is narrow in cities with small annual temperature amplitude.
- Inhabitants in central Europe, where the annual sunshine duration is low, usually prefer more sunshine, even when its actual value (*G*) is strong, unlike people in southern Europe, where they don't prefer more sunshine even when its actual value is weak.

The gender-related findings of this study are as follows:

- European women tend to perceive thermal conditions neutral under slightly warmer thermal conditions than men. This applies more for the lower and less for the upper thresholds of the neutral *PET* zone.
- Females have greater sensitivity to the changes of the environmental conditions evidenced by the narrower neutral *PET* zone and the stronger correlation between their sun preference and the actual value of solar radiation. However, they tend to expose themeselves more to the sun than males.

Outdoor space design that can enhance and support adaptive opportunities is essential in visitors' thermal comfort. A diverse space-morphology that provides opportunities for relaxation both in the sun as well as under natural and artificial shading elements is of primary importance as they allow visitors to choose several options depending on the background conditions, i.e. their subjective perception of these conditions. Shading is essential not just in a hot climate but the temperate climate of the rest of Europe as well. For warmer climates design enabling outdoor activities even after sunset is also important as the climate supports outdoor activities later in the evening, when comfort levels are increased.

Last but not least, the limitations of the present study should be mentioned. The first limitation is the heterogeneity of such a combined dataset. Although it is by far the most comprehensive OTC dataset for different European cities, and we sought to ensure the comparability of the data analyses methods and the derived results, admittedly drawbacks of the dataset, e.g., lack of data for some cities in summer will induce uncertainties to the research findings. Nevertheless, the study aims to set up a framework for *meta*-analysis of OTC research and draw attention to the gender-related tendencies emerged. In this sense, it is believed that with more comprehensive data, i.e., data obtained from systematic survey campaigns with unified protocols, more prominent findings could be derived, and more detailed analysis such as seasonal comparison across different cities could be carried out. The second limitation is the use of neutral temperature which is easily standardized and commonly adopted in the literature. Over the past years we have learned that the neutral temperature may not necessarily be the temperature subjects feel comfortable, or the preferred temperature. The offset of thermal comfort from thermal neutrality involves the issue of thermal alliesthesia, which is beyond the scope of the present study and definitely requires thorough investigation in the future work.

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.

Acknowledgements

This study is supported by the National Key Research and Development Program of China (Project No.: 2017YFC1503001). The authors would like to gratefully thank the two anonymous reviewers for their very constructive comments which have indeed helped to significantly improve this paper.

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