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REVIEW PAPER

Thermal sensation in outdoor urban spaces: a study in a Tropical Savannah climate, Brazil

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Abstract

The present study carried out assessments regarding thermal sensations under different weather conditions in three urban areas in Cuiabá, Brazil, a Tropical Savannah climate (Aw) region. Thermal acceptability by means of thermal sensation votes (TSV) was addressed based on the estimation of the Universal Thermal Climate Index (UTCI) values. Important issues related to clothing thermal insulation (Icl), the effect of gender on thermal sensation, and implications of artificial conditioning (AC) systems are also evaluated. Micrometeorological variables were determined and 685 questionnaires were applied to evaluate individual pedestrian thermal preferences. The Icl observed in the Tropical climate was lower than that intrinsically inputted by the UTCI for Temperate climates. The local thermal comfort zone ranged between 21.5 and 28.5 °C, with both thresholds higher than those observed in studies conducted in Subtropical, Mediterranean, and Continental Temperate climates while the local hot thermal sensation categories were displaced at least 3 °C above than those for the aforementioned climates. The effect of gender on thermal sensation indicated that females are more sensitive to cold stress conditions than males, requiring higher Icl for temperatures below 28 °C. The physiological adaptation by continuous exposure to AC systems reduced the neutral temperature between AC and non-artificial conditioning system users (NAC) by 0.8 °C, with more intense differences in hot TSV ranges. This study reveals differences between stated TSV classes derived for other climates and those resulting from TSV declared by Savannah local residents, indicating that local thermal sensation scale for UTCI in an important key for environment planning.

Keywords Urban climate · UTCI Index · Outdoor thermal comfort · Gender thermal sensation · Air conditioning acclimatization

Introduction

According to the World Health Organization, over half of the world's population lives in town and cities, and this is expected to reach 68% in 2050, with a 2.5 billion increase in urban populations during the current century (United Nations 2018). Therefore, thermal indices are important, as they provide a tool to estimate the thermal quality of urban spaces and allow for the minimization or neutralization of risks concerning excessive exposure to heat and cold stress. Moreover, knowledge on exposure levels is crucial to develop guidelines for the improvement of urban ambience related to outdoor activities, such as sports, social living, and recreation. In addition, it is important to use thermal indices as tool to forecast thermal health hazards, especially in outdoors conditions, as well as in the prevention of related disasters, such as heat waves (Pappenberger et al. 2015).

The Physiological Equivalent Temperature (PET) (Höppe 1999) and the Universal Thermal Climate Index (UTCI) are rational indices, based on the human energy balance, developed in the last years to predict thermal stresses (Błażejczyk et al. 2010). The latter represents the air temperature (Ta) which produces the same thermal strain as a true thermal environment under reference conditions. The reference environment is equivalent to the external environment, with an air temperature

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(Ta) equal to the mean radiant temperature (Tmrt), a wind speed of 0.3 m s^{-1} at pedestrian level (0.5 m s^{-1} at 10 m height) and vapor pressure (va) at 50% for a person moving at a speed of 4 km per hour (1.1 m s^{-1}), equivalent to a metabolic rate of 135 W m^{-2} (2.3 MET) (Błażejczyk et al. 2010). The UTCI comprises an intrinsic adjustment clothing model insulation dependent on ambient temperature, and considers seasonal clothing adaptation habits based on field data derived from European surveys. It is supposed to be a realistic representation of behavioral actions that affect the human perception of the outdoor climate. The UTCI equivalent temperature has been categorized in terms of thermal stress, based on physiological criteria. The limits for "No Thermal Stress" have been defined as ranging between 9 and 26 °C and UTCI values between 18 and 26 °C may comply closely with the definition of the "thermal comfort zone" (Havenith et al. 2012; Błażejczyk et al. 2010).

Since the UTCI index was developed, investigations have been conducted in several cities with different climates, assigning thermal sensations to UTCI values. Rossi, Kruger, and Bröede (2012) applied the UTCI to define the local thermal comfort zone and discomfort scales for the Subtropical climate region (Cfb-Köppen-Geiger) in southern Brazil, which presents cold winters and warm summers. The clothing adjustment was observed in the field (Icl) fitted to that inputted in the UTCI model, demonstrating the adequate predictive capacity of the UTCI model, with the "No Thermal Stress" scale ranging between 15 and 27 °C. On the other hand, Pantavou et al. (2013), when assessing the local thermal sensation of a population in a Mediterranean climate with hot summers (Csa), observed that the thermal clothing insulation obtained in the field (Icl) was related to air temperature (Ta) and was consistent with the UTCI model. The "No Thermal Stress" class ranged between 17.5 and 24.5 °C, revealing that the lower limit was higher, while the upper limit was lower than the original UTCI scale. In addition, Lai et al. (2014) investigated outdoor thermal comfort in a park in Tianjin, China, displaying a Humid Continental climate, characterized by dry winters and hot summers and influenced by monsoons (Dwa). The local "No Thermal Stress" scale was found within 12 °C and 25 °C, close to the original range. Finally, Huang et al. (2016) conducted a local thermal sensation study using the UTCI in six outdoor spaces in Wuhan, China, a city characterized by a Humid Subtropical climate (Cfa). The upper limit of the local thermal comfort zone was of 28.8 °C, while the lower limit was 15.2 °C, indicating greater adaptability imposed by the Humid Subtropical climate.

The current study was carried out in a Tropical Savannah climate, the second most common climate category worldwide, covering 11.5% of the globe's land area (Huang et al. 2016), 60.1% of South America (Peel et al. 2007), and 81.4% of Brazilian territory (Álvares et al. 2013). The climate is characterized by high air temperatures throughout the year, wide hygrothermal variations, and undefined or absent winter seasons. Despite such extensive coverage, few studies have been conducted to understand thermal sensation in outdoor spaces in Tropical climate regions, especially in South America. In Brazil, an application of the UTCI index was conducted at Cuiabá city (Aw), and indicated that weather conditions in September were responsible for the highest heat stress under open sky conditions (Callejas, Durante e Nogueira 2013). Lucchese et al. (2016) evaluate the ability of the UTCI to predict heat stress conditions in a public square at Campo Grande city (Aw) during hot and cold seasons. The UTCI displayed a relatively satisfactory performance due to the regional acclimatization influence. In Rio de Janeiro (Am), Krüger, Drach, and Bröde (2015) identified significant thermal sensation vote differences among groups of respondents who reported not having and having access to air conditions units (or central systems) at home and/or at work. The same researchers observed that urban geometry (expressed by the sky-view factor—SVF) may affect passerby thermal perceptions in outdoor microclimates in downtown Rio de Janeiro (Krüger, Drach, and Bröde 2016).

Due to the warm weather conditions imposed by the Tropical climate, the local population has increasingly uses artificial air conditioning to reduce indoor heat. Hence, individual thermal history may be key, since studies have demonstrated that people who use artificial air conditioning (AC) may display affected thermal tolerance due to constant use, presenting lower tolerance to hot stress conditions than those who live in naturally ventilated or non-artificial conditioning (NAC) environments (Busch 1992; Krüger et al. 2015). Thus, it is important to assess the thermal history interference concerning individual thermal perceptions when designing or re-qualifying open urban spaces to make them attractive, in order to encourage physical activities and improve the physical and mental health of town dwellers (Thach et al. 2015).

The consideration of how people interact and perceive the thermal environment is an important issue, as this knowledge improves the chances of adequately designing outdoor urban spaces for users. Thus, the thermal acceptability of Tropical Savannah climate by means of thermal sensation votes is addressed herein, using UTCI as a measure of biothermal conditions in the environment and assigning thermal sensations to UTCI values. This study also investigates whether clothing adjustments observed in field campaigns is similar to that intrinsically inputted in the UTCI and if individual thermal history influences the definition of local thermal sensation scales, by taking into consideration that the population's heat resilience is inversely proportional to the time it remains exposed to air-conditioned environments.

Materials and methods

Study area

Cuiabá (15° 36′ 36″ S; 56° 11′ 04″ W), the capital city of the state of Mato Grosso, is located in the Central-Western region of Brazil (see the graphical location of the city in Online Resource 1), with an estimated population of 580,489 inhabitants (IBGE 2016). The region is surrounded by two ecosystems: wetlands to the south (Pantanal) and Savannahs to the north (Cerrado). It is located in the geomorphological province called "Baixada Cuiabana," with altitudes varying between 146 and 259 m above sea level (Callejas et al. 2016).

The climate type in the region is Tropical Semi-humid climate or Tropical Savannah climate (Aw) (Köppen-Geiger classification), with two distinct seasons: a hot and humid season between Spring and Summer (October to April) and a hot and dry season between autumn and winter (May to September). The mean annual temperature is 26.9 °C and the average, minimum, and maximum annual air temperatures (27.9 °C, 23.0 °C, and 32.9 °C, respectively) during the wet season are higher than in the dry season (25.5 °C, 18.7 °C, and 32.5 °C, respectively). Mean annual relative humidity is 71.6% and the average annual values observed during the wet and dry seasons are of 75.9% and 65.5%, respectively. The mean annual precipitation is of 1344.9 mm with most accumulation occurring in the wet season (1216.3 mm), with low values observed during the dry season (128.6 mm) (Machado et al. 2015). Winter (May and July) is characterized by cold fronts caused by the advance of the South Atlantic Polar Mass (locally called "friagens"), leading to air temperatures below 18 °C at an average of eight days per year (Campelo Júnior et al. 1991).

Field survey

Environmental variables were monitored from 7 am to 8 pm (local time) and standard questionnaires were applied to investigate thermal sensation and pedestrian preference within a wide range of meteorological conditions. The survey periods took into account the typical seasons observed in the area, between March 2016 and April 2017, following UTCI application recommendations (Błażejczyk et al. 2010). In the first phase, five campaigns were carried out during the fall season, where 279 pedestrians were interviewed, at a square located at the Mato Grosso Federal University campus. In the second phase, another four campaigns were conducted during winter, where 213 pedestrians were interviewed at an avenue in the commercial and institutional district. The third and last phase occurred in the summer, totaling four campaigns and comprising the application of 230 questionnaires to pedestrians located downtown (view graphical location and characteristics of surrounds sites in Online Resource 2). The selected regions are characterized by a high frequency of people (males, females, young, adults, and elderly) walking in the street, allowing for an adequate representation of the local urbanites. A total of 685 valid questionnaires were obtained, statistically adequate to characterize the urban population of the studied area (Dowdy et al. 2004).

Pedestrians were randomly selected for the application of a questionnaire adapted from the ISO 10551 standard (1995) and were asked to inform personal data (gender, age, height and weight), information concerning residence time in the city, walking time, and health status. Clothing thermal insulation was estimated according to a look-up table with typical clothing garments using the ISO 9920 standard (2007). Inclusion criteria consisted of respondents who had lived in the city for at least 6 months (ASHRAE55 2004), who were walking for at least 15 min, and who declared themselves free from disease symptoms. The respondents were asked to declare their thermal sensation, thermal preference, and thermal acceptability of the thermal environment (ISO 10551, 1995). The thermal sensation vote (TSV) was based on the 7-point symmetrical scale proposed by the ISO 10551 standard (− 3, cold; − 2, cool; − 1, slightly cool; 0, neutral; + 1, slightly warm; + 2, warm; + 3, hot). A 7-point preference scale was employed for thermal preference (which comprises a central point of indifference—absence of sensation—and two times 3 degrees of increasing intensity), while direct assessments (acceptable, unacceptable) were used for thermal acceptability. The interviewees were asked whether they use air conditioning system (AC-user or non-AC users) at home or at work and, if so, how long they remained indoors with artificial air conditioning, according to three time length categories—less than 4 h, between 4 and 8 h and over 8 h) (view outdoor thermal comfort questionnaire in Online Resource 3).

Meteorological measurements and instrumentation

Meteorological variables were determined by using a mobile HOBO micro weather station installed close (at approximately 2 m) to the interviewees. The station was equipped with a solar radiation sensor (Rg), air pressure (pa), air temperature (Ta), relative humidity (RH), globe temperature (Tg), and wind speed (va), measured at 2 m above the ground. Wind speed was then adjusted to 10 m height as the recommendation established for the UTCI index reference environment using the ASHRAE handbook equation (Eq. 1) (ASHRAE 1997) where v_{a2} is the wind speed measured by the anemometers (m/s), α is the mean speed exponent, set to 0.33 for city-center areas, z is the distance from the ground (10 m is the height), z' is the height of the anemometers installed above the ground (2 m in our research), and finally v_{a10} is the wind speed at a height of 10 m above the ground (m/s).

$$va_{10} = va_2\left(\frac{z}{z'}\right)^{\alpha} \quad (1)$$

All other instruments were installed at a height of 1.1 m, corresponding to the mean height of an adult center of gravity (ISO 7726, 1998). Mean radiant temperature (Tmrt) was calculated by the equation for forced convection (Eq. 2), according to ISO 7726 (1998). The diameter (D) of the black-globe thermometer (ε_g assumed equal to 0.95) used in the research was of 0.063 m.

$$\text{Tmrt} = \left\{(\text{Tg}-273)^4 + \left[\frac{(1.1\times10^8\times va^{0.6})}{(\varepsilon_g\times D^{0.4})}\right]\times(\text{Tg}-\text{Ta})\right\}^{1/4} - 273 \quad (2)$$

Sampling was set at 30 s for the HOBO Data logger and averaged every 5 min. Climatic variables were monitored according to ISO 7726 (1998) standards and sensors were calibrated prior to the campaign. Most of the interviews (87% of the sample) were conducted before 10 am and after 3 pm in order to avoid overestimating Tmrt values when the black globe was used (Khrit et al. 2017).

Data analysis methodology

Due to its universality and indication for all types of climates, the Universal Climate Thermal Index (UTCI) was employed to access the thermophysiological effects of the thermal environment and predict the heat stress of pedestrians during the interviews. The UTCI is a non-steady state index, based on the multi-node human thermoregulation model proposed by Fiala, Lomas, and Stoher (1999). It combines an adaptive clothing model and the concept of equivalent temperature. The UTCI was calculated using the BioKlima software v.2.6 (IGiPZ PAN 2018).

Microclimatic parameters, personal data (age, gender, weight, and height), clothing insulation, and AC and non-AC users were treated as independent continuous or nominal variables, likely to affect the dependent ordinal variable of thermal sensation vote (TSV). Clothing thermal insulation, retrieved from the questionnaires, was fitted by a Local Regression Analysis (LOESS) (Zuur et al. 2009) to air temperature, in order to describe and compare the average course of clothing thermal insulation between populations in Temperate and Tropical climates. Data were stratified by gender to identify potential statistically significant difference between male and female average clothing thermal insulation and to relate them to the thermal sensation vote.

The local comfort zone and thermal TSV scales were derived according to questionnaire responses, considering environment thermal perception and preferences, expressed by the thermal sensation vote (TSV). Therefore, the thermal comfort zone may be defined according to pedestrian votes when they stated neither feeling cold nor feeling hot stress during the interviews (vote 0) and when declaring themselves comfortable with the thermal environment. Additionally, pedestrians, who felt slightly cold (− 1) or slightly warm (+ 1) but at the same time declared to be comfortable within the thermal environment, were also included in the analysis. On the other hand, hot and cold thermal stress discomfort scales were derived when the respondents declared themselves feeling slightly warm (vote + 1), warm (vote + 2) or hot (vote + 3), and slightly cool (vote − 1), cool (vote − 2), or cold (vote − 3).

The mean thermal sensation vote (MTSV) was calculated by applying the methodology proposed by De Dear and Brager (1998), at 1 °C UTCI intervals, in order to estimate the UTCI range based on the stated votes. At least five respondents were used for each grouped thermal sensation vote average for each 1 °C interval (UTCI), to avoid biased thermal sensation votes. This procedure generated a scatter plot between mean thermal sensation vote (MTSV) (y-axis) and mean UTCI values (x-axis), from which a linear regression curve was fitted. This was carried out due to its simplicity and the fact that non-linear regressions curves failed to provide significantly more precise adjustments, evaluated by the coefficient of determination (R^2) (Pantavou et al. 2014). This adjusted linear equation was used to determine the neutral temperature (with TSV = 0) and to obtain local thermal sensation scales of the Tropical respondents, derived from the UTCI values. Values between − 0.5 to + 0.5 were considered as thermal acceptability condition (neutral zone). In the case of cold TSV classes, values between − 0.5 and − 1.5 were defined as slightly cool and values below − 1.5 indicate a cold condition. In the case of hot TSV classes, the range between + 0.5 and + 1.5 was considered slightly warm, between + 1.5 and + 2.5 as warm and above + 2.5, hot. As UTCI scale is based on intensity changes of specific physiological parameters (e.g., sweating, skin temperature, skin blood flow), its original scales, categorized in terms of thermal stress, reflects an approach that looks at responses to reference conditions and deducts the load caused by the organism's physiological response to actual environmental conditions (Błażejczyk et al. 2010). Therefore, it describes thermal load in humans, instead of describing pedestrian's thermal sensations during the campaigns. Thus, the current study develops local thermal sensation scales, using linear regression to attribute to particular TSV corresponding UTCI values.

The procedures established by De Dear and Brager (1998) were also applied to predict the percentage of dissatisfied people (PD) for every mean thermal sensation vote (TSV) 1 °C interval. The PD regression line for the Tropical climate population was compared with the PD suggested by the ISO 7730 standard (2005). Subgroups of thermal sensation votes by males/females and AC/non-AC users were also averaged for every 1 °C in the UTCI range based on the votes, in order to account for gender and air conditioning influences on thermal perception.

The thermal perception distribution does not usually follow a normal distribution. Thus, the Wilcoxon-Mann-Whitney *U* test, a non-parametric test applied to two independent samples, was performed (calculated by means of raw data), to identify statistically significant differences ($p < 0.05$) between the evaluated subgroups (Tropical vs. Temperate clothing thermal insulation models; thermal sensation males vs. females; thermal sensation AC users vs. non-AC users) (Zuur et al. 2009). The observed linear trends between subgroups were statistically tested by variance analysis (Meyer and Seaman 2014), confirming the significance of the linear models tested in the research ($p < 0.01$).

Results

Weather conditions

Climatic variable fluctuations recorded during the field campaigns were consistent with synoptic regional climate patterns. The highest air temperature/mean radiant temperature was observed during the summer measurements, while the lowest air temperatures were observed during the winter and intermediate temperatures, during the fall, a transitional weather period (see data in Online Resource 4). Winter measurements were carried out during the occurrence of cold fronts to assess cold stress conditions that would justify the lowest air temperature recorded during the period. However, alternations between low, moderate, and high air temperatures were common during the winter. Wind speed followed a regional pattern, at low intensities (Cuiabá is a city located within a depression), but the elevated surface roughness of the urban sites, due to buildings and trees, contributed to further reduce wind speed. The lowest heat stress predicted by the UTCI index occurred during the winter, at 14 °C, and the highest in the summer, at 45.4 °C.

Personal variable descriptions

The mean biometric data of the respondents were classified according to the World Health Organization (1995) (see data in Online Resource 5). The female prevalence of the interviewees (54.6%) was consistent to the 2015 Brazilian population census (48.4% males and 51.6% females), while 61.1% of the sample ranged within 25 to 64 years old. Even though the percentage of healthy people was higher than overweight and obese ones, the mean body mass index (BMI) was of 25.41, confirming a Brazilian population trend towards overweight conditions (Brasil 2016).

A significant variability in age (7 to 86 years), weight (28 to 122 kg), and thermal cloth insulation (0.1–1.47 clo) of male and female pedestrians during the campaigns was observed (see data in Online Resource 6). A gender analysis indicated higher mean age for females compared with males. On the other hand, the male group presented higher height and weight than the female group. These data agree with the average rates established by ISO 8996 (2004). Higher thermal insulation in the female group (0.5 clo) compared with the male group (0.45c lo) was recorded.

Clothing thermal insulation

Clothing model observed in the field for a Tropical climate

The clothing thermal insulation used by the interviewees during the campaigns ranged between 0.12 and 1.47 clo for temperatures between 13.9 and 37.5 °C. These data were correlated to the air temperature noted during the interviews, in order to retrieve a clothing model adjustment for a Tropical climate (Icl/Trop), assessed by a Loess local regression with a third order polynomial equation (Fig. 1a).

In the case of air temperatures below 24.5 °C (intersection point between the two adjustment models), the Icl/Trop model presented 0.18 clo of mean absolute difference in relation to Icl/UTCI, providing lower clothing isolation than those indicated for Temperate climate populations ($p < 0.05$). Above this temperature, the Icl/Trop model continuously decreased until 30 °C, finally stabilizing, providing a minimum insulation of approximately 0.4 clo, compatible with the intrinsic clothing insulation model inputted in the UTCI index. Between 24.5 and 30 °C, the Icl/Trop model provides higher isolation than the Icl/UTCI model (0.41 clo of mean clothing isolation), although a lower mean absolute difference is observed (only 0.07 clo). In turn, the intrinsic UTCI model also continues its decrease, leading to values lower than 0.4 clo for temperatures above 26.1 °C and becoming negative at 31.6 °C. Due to this behavior, the Icl/UTCI model was set to a minimum isolation of 0.4 clo at 26.1 °C. A statistical analysis indicated no significant difference between the Icl/Trop and the intrinsic Icl/UTCI models for temperatures above 24.5 °C ($p > 0.05$).

Clothing model adjustment for gender

During the campaigns, clothing isolation for the female group ranged between 0.22 and 1.47 clo (average 0.5clo), while those for the male group varied from 0.12 to 1.09 clo (average 0.46 clo), displaying a statistical difference ($p < 0.05$). Thus, the Loess local regression was employed for these subgroups to evaluate clothing model adjustment of a Tropical population by gender (Fig. 1b). In the case of temperatures above 30 °C, almost the same mean level of insulation was observed for both gender groups and low dispersion with regard to mean isolation (0.40 ± 0.08 clo). However, below 30 °C, the female group

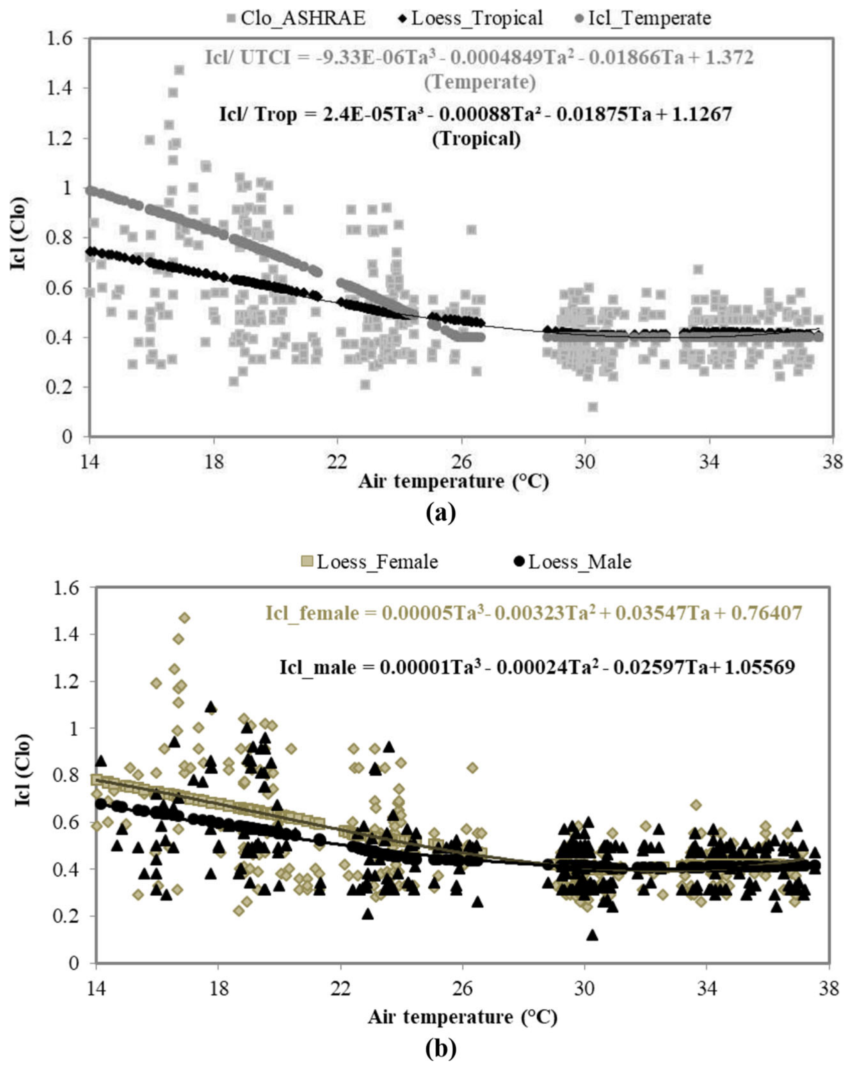


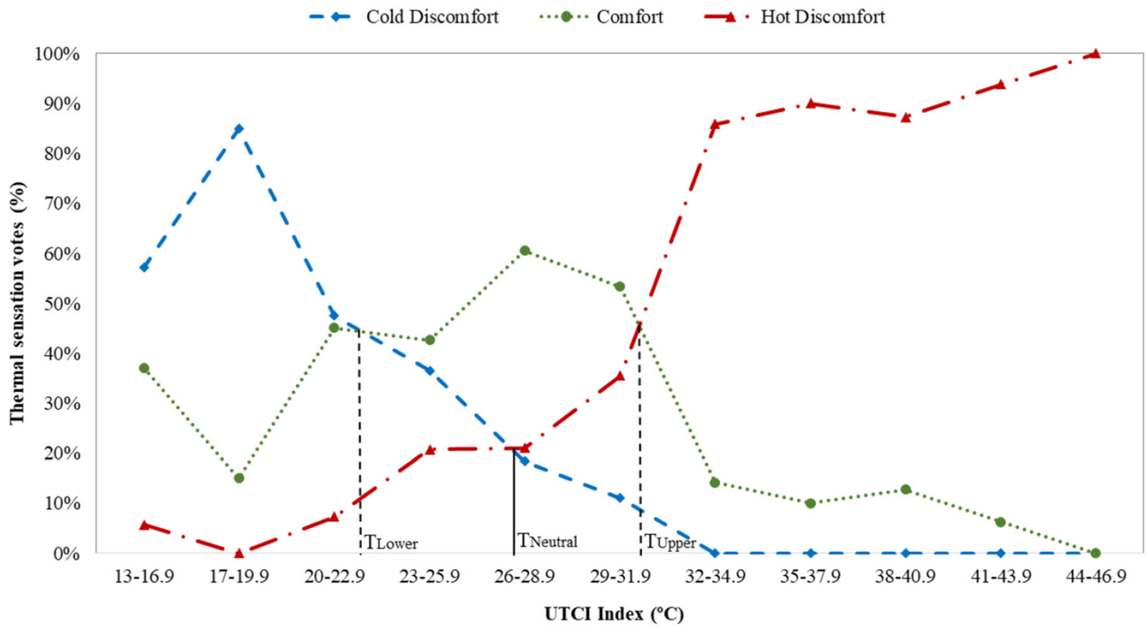
Fig. 1 **a** Pedestrian clothing model adjustment (Icl) for different air temperatures in Temperate and Tropical climates and **b** clothing adjustment insulation (Clo) by gender

(0.55 ± 0.22 clo) preferred more clothing thermal insulation than the male group (0.50 ± 0.17 clo).

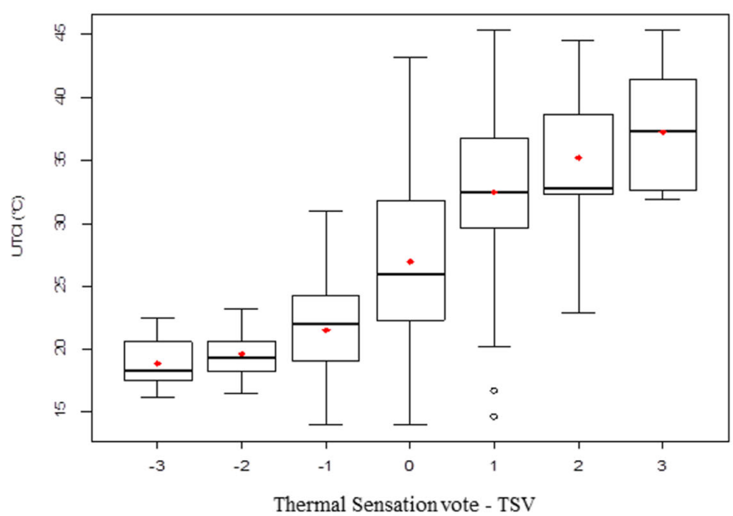
Relationship between thermal sensation vote and Universal Thermal Climate Index

Figure 2 a demonstrates the percentage of thermal sensation vote (TSV) and values derived by the UTCI model. The percentage of people feeling cold thermal discomfort decreases as UTCI values rise. On the other hand, heat thermal discomfort decreases as UTCI values decrease. The highest percentages of respondents declaring themselves in thermal comfort are concentrated on the central scales of the green line of the *x*-axis. The intersection between the fitted cold (blue line) and comfort (green line) curves (20–22.9 °C, in UTCI units) define the lower limits (T_{Lower}) expected for the thermal comfort zone, while an intersection between the fitted comfort (green line) and hot (red line) defines the upper limit (T_{Upper}) (29–31.9 °C) (see black solid lines in Fig. 2a). The inclusion of the comfort zone within these limits is reinforced by the fact that the fitted comfort line in these intervals undergoes abrupt modification with regard to the angular coefficient, indicating that satisfaction progressively reduces as thermal stress levels rise in cold and hot environments, respectively. The intersections of the cold and hot discomfort lines represents the temperature at which individuals have the same perception of discomfort (both at a level below 20%). Thus, the neutral temperature lies almost in the end of the interval between 23 and 26 °C (T_{Neutral}) (black solid line, Fig. 2a).

The relationship between UTCI and TSV is illustrated by the boxplot graph displayed in Fig. 2 b. The temperature ranges are generally widely distributed for each box, and the median UTCI values (red dot) increase with increasing TSV scores. Thermal comfort sensation votes (0) ranged between 13 and 43 °C of the UTCI,



(a)



(b)

Fig. 2 **a** Frequency distribution of thermal sensation votes for comfort, cold, and hot discomfort vs the UTCI index and **b** the UTCI index as a function of thermal sensation votes (TSV) declared by respondents

with the first and third quartiles concentrated between 22.3 and 31.8 °C, respectively. This corroborates the limits identified in Fig. 2 a. Thermal slightly cold discomfort votes (− 1) ranged between 13 and 31 °C, with the first and third quartiles between 18.8 and 24.3 °C, overlapping the thermal comfort declaration, with a statistical difference between these two groups ($p < 0.05$). Thermal slightly warm discomfort votes (+ 1) also presented high variability, ranging from 13 to 45 °C, with the first and third quartiles between 29.6 and 36.9 °C, also overlapping the thermal comfort scale declaration, with a statistical difference between these categories ($p < 0.05$). Thermal warm discomfort votes (+ 2) presented a lower range, between 22.8 and 44.5 °C, with the first and third quartiles between 32.3 and 38.7 °C and a significant difference for the slightly warm thermal sensation ($p < 0.05$). On the other hand, no statistical differences between hot (+ 3) and warm thermal sensation (+ 2) ($p > 0.05$) and between cold (− 3), cool (− 2), and slightly cool (− 1) thermal sensation ($p > 0.05$) were observed. The non-definition for cold and cool thermal sensations is related to the low number of votes during cold conditions and to the low occurrence of cold days during the campaign.

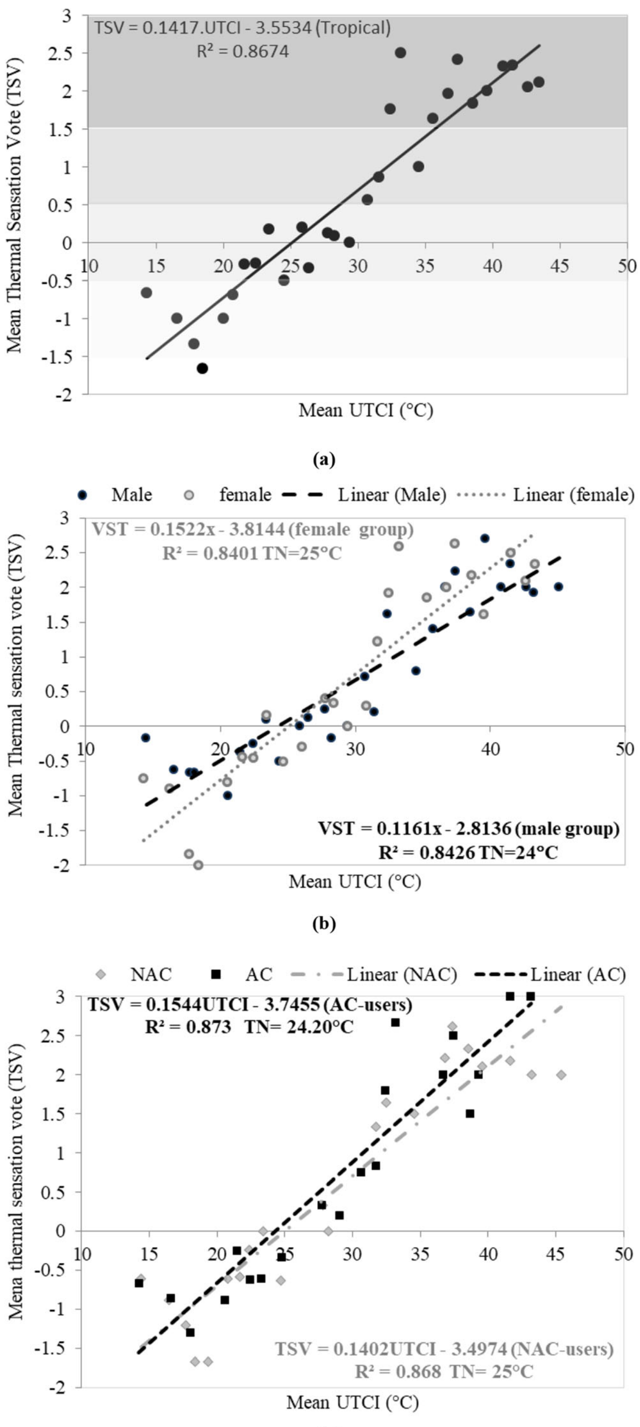


Fig. 3 **a** Mean thermal sensation vote in relation to 1 °C UTCI interval for all collected data, for **b** data stratified by gender, and **c** data stratified by air conditioning system use (AC or non-AC users)

Thermal sensation acceptability for Tropical Savannah climate residents

Mean thermal sensation vote for all collected data

Mean thermal sensation vote values were correlated to UTCI index values within a 1 °C UTCI variation (binned data), to minimize variations among interviewees in terms of subjective thermal assessment (Fig. 3a). The angular coefficient predicted by the correlation was of 0.1417 TSV/1.0° UTCI. The inverse value of this coefficient (slope) corresponds to 7.0 °C UTCI for each 1.0 TSV variation. The fitted linear regression line shows the UTCI value in which people feel neutral environmental conditions (TSV = 0) is of 25 °C. It is important to note that the present study dealt with pedestrian thermal sensation with a low metabolic rate variation, as only pedestrians walking approximately at 4 km/h (1.1 m/s) on streets for at least 15 min were selected for the interviews (Krüger and Tamura 2018).

Table 1 presents the local TSV limits adapted for a Tropical Savannah climate, derived from the linear regression line shown in Fig. 3 a. The discrepancies between the limits are clearly perceptible when comparing the thermal comfort zone limits adapted for a Tropical climate and those established for Subtropical, Mediterranean, and Continental Temperate climates, demonstrating climatic adaptations among different populations.

Thermal sensation by gender

Thermal sensation votes by gender were correlated to mean UTCI values, with an increment of 1 °C (Fig. 3b), despite no significant difference between male and female subgroups ($p > 0.05$). Linear regression lines indicated distinct behavior due to the angular coefficients and independent terms. In the case of the female subgroup, the angular coefficient was 0.152, corresponding to 6.6 °C in each 1.0 TSV variation, and of 0.116 in the case of males, corresponding to 8.2 °C. Female neutral temperature was determined at 25 °C, whereas the male neutral temperature is slightly lower, of 24 °C, revealing that the latter group is more resilient and less sensitive to thermal environment variations than the former.

Influence of air conditioning on acclimatization

Based on the fact that individual thermal history regarding the use of air conditioning may influence thermal perception, respondents were questioned about the use and permanence in air-conditioned environments (at home and at work). This specific item was added to the questionnaire when the survey was already in progress, restricting the sample to 415 interviews. About 254 interviewees replied that they did not use air conditioning (NAC) in any environment, against 161 who

Table 1 European temperate thermal stress categories defined for UTCI index and local thermal sensation categories for Subtropical, Mediterranean, Continental Temperate, and Tropical Savannah climates

Stress classes	Original UTCI ranges Blazejczyk et al. (2010)	UTCI ranges Subtropical Rossi et al. (2012)	UTCI ranges Mediterranean Pantavou et al. (2013)	UTCI ranges Temperate Continental Lai et al. (2014)	UTCI ranges Tropical Savannah
Extreme cold stress	< – 40 °C	–	< 4.1 °C	< – 21 °C	–
Very strong cold stress	– 40 to – 27 °C	–	4.1 to 5.9 °C	– 21 to – 16 °C	–
Strong cold stress	– 27 to – 13 °C	–	5.9 to 9.1 °C	– 16 to – 11 °C	–
Moderate cold stress	– 13 to 0 °C	–	9.1 to 14.0 °C	– 11 to – 6 °C	< 14.5 °C
Slightly cold stress	0 to 9 °C	< 15 °C	14.0 to 17.4 °C	– 6° to 12 °C	14.5 to 21.5 °C
No thermal stress	9 to 26 °C	15 to 27 °C	17.4 to 24.5 °C	12 to 25 °C	21.5 to 28.5 °C
Moderate heat stress	26 to 32 °C	> 27 °C	24.5 to 29.1 °C	25 to 33 °C	28.5 to 36 °C
Strong heat stress	32 to 38 °C		29.1 to 34.1 °C	33 to 39 °C	36 to 43 °C
Very strong heat stress	38 to 46 °C		34.1 to 37.7 °C	39 to 47 °C	> 43 °C
Extreme heat stress	> 46 °C		> 37.7 °C	> 47 °C	–

declared that they used air conditioning (AC) either fully or partially at home or/and at work.

The statistical analysis indicated significant differences between the thermal perceptions of NAC and AC groups ($p < 0.05$), confirming the heterogeneity of vote distribution. Therefore, the mean thermal sensation votes by NAC and AC groups were correlated to mean UTCI values for 1 °C (Fig. 3c). The angular regression coefficient predicted for the NAC group was of 0.140, corresponding to 7.1 °C UTCI for each 1.0 TSV variation, the AC group presented an angular regression coefficient of 0.154, corresponding to 6.5 °C UTCI/TSV. This indicates that people who use air conditioning are more sensitive to thermal variations than those who do not.

Percentage of dissatisfied respondents

Thermal acceptability was obtained by directly asking the respondents whether outdoor thermal conditions were acceptable. The mean declared percentage of dissatisfied (PD) people was correlated for each 1 °C interval of mean thermal sensation vote (TSV). A second-degree regression line was used to represent data behavior. The correspondent coefficient of determination (R^2) was equal to 0.7658 (Fig. 4).

Data on the percentage of dissatisfied people (PD %) were adjusted to the Fanger's equation model, expressed in terms of percentage of dissatisfied (PD) people (ISO 7730, 2005). Criteria demanded that the adjusted curve should present the same respondent percentage of dissatisfied people (6.32%) for the thermal neutrality condition (TSV = 0), while errors in the data decrease when the mean squared error (RMSE) was taken into account (see data in Online Resource 7).

Discussion

Clothing thermal insulation model (Icl/trop) estimated by the field data displayed a weak correlation with the intrinsic Icl inputted into the UTCI index (Icl/UTCI), as proposed by Blazejczyk et al. (2010), and statistical differences were confirmed ($p < 0.05$). Differences were also observed from Subtropical (Rossi et al. 2012) and Mediterranean climate (Pantavou et al. 2013) models at temperatures below 24.5 °C. These findings were unexpected and contradicted the initial hypothesis that people in Tropical climates would wear heavier clothing insulation at lower air temperatures due to their lack of acclimatization to cold stress conditions. A

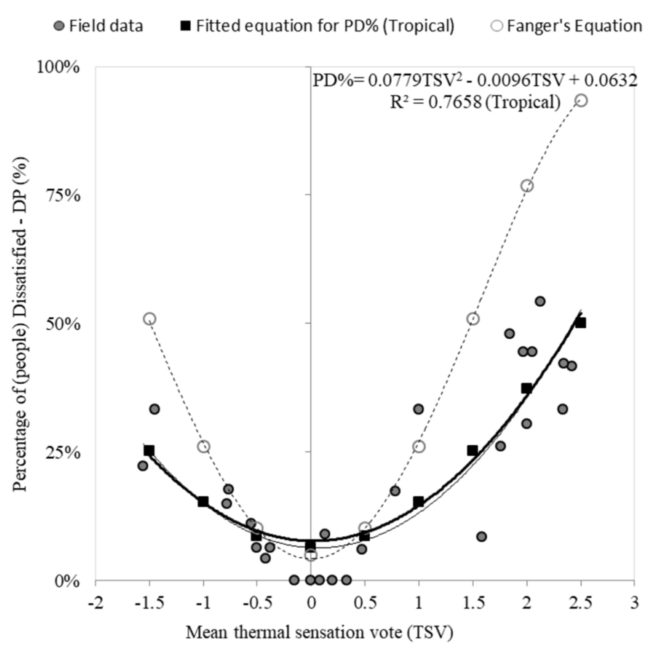


Fig. 4 Percentage of dissatisfied (PD) people curve for a Tropical climate

possible explanation may be the absence of adequate clothing insulation for cold stress conditions, since interviewees wore overlapping light clothing during the field campaign. This behavior may also be explained by the relatively low number of days presenting temperatures below 18 °C in the region. In fact, people yearn for the first cold days of the season, as a form to relieve the constant hot stress conditions observed throughout the year. Actually, the Tropical Savannah climate is characterized by a non-defined winter season.

The derivation of clothing thermal insulation model between genders revealed that females require more clothing insulation at air temperatures below 30 °C (curve intersection point) compared with males. The female population also required more clothing insulation than the male population in south Brazil (Subtropical climate, Cfb-Köppen), although only for air temperatures below 24 °C (Rossi et al. 2012), and no statistical difference was found between the two populations. This demonstrates acclimatization of the Brazilian south population to a cold climate. No statistic differences between gender thermal insulation were reported in other studies, such as that carried out by Pantavou et al. (2013) in the Mediterranean climate. Females also presented the highest dispersion data with regard to mean clothing insulation, probably due to the great variety of clothing compared with that used by males. Taking into consideration this behavior, the male group was more resilient to neutral and cold stress conditions than the female group in the campaigns, since the former required less clothing thermal insulation.

The correlation parameters established between mean thermal sensation vote and UTCI values reinforce an adaptation of the Savannah Tropical population to heat stress climatic conditions. Studies conducted in Athens (Greece-Csa), Tianjin (China-Dwa), and Wuhan (China-Cfa) (Pantavou et al. 2013; Lai et al. 2014; Huang et al. 2016) registered higher slopes than those observed in the current study (approximately 8 °C/TSV). This implies that neutral temperatures (20.3, 17.5, and 22 °C, respectively) are lower than those observed for inhabitants residing in Savannah regions (25 °C). These differences are related to the need of the population to acclimatize to wide thermal stress variations throughout the year, due to well-defined seasons in the aforementioned countries. This is not observed in Tropical regions, where high air temperatures prevail throughout the year and winter is not well defined. In Rio de Janeiro (Brazil) (Am), the slope coefficient (0.1404) and neutral temperature (23.5 °C) were reported as close to those observed in the current study (Krüger, Drach, and Bröde 2015).

Based on thermal load in humans, the limits for UTCI thermal comfort zone attributed to European are categorized between 18 and 26 °C (Błażejczyk et al. 2010). In turn, those zones retrieved by local thermal perception differ between regions mainly because of thermal acclimatization. For Chinese populations, range is extremely flexible (between 12 and 25 °C) due to the climatic variations in this region (Lai et al. 2014). On the other hand, limits for the Subtropical climate in south Brazil (15–27 °C) (Rossi et al. 2012) and the Mediterranean climate in Athens (17.4–24.5 °C) (Pantavou et al. 2013) are closer to those observed for Tropical regions (21.5–28.5 °C), in spite of the fact that they present smaller amplitudes tending towards higher temperatures, due to their correspondent geographical positions near the tropics. Note that residents in Tropical climate feels comfortable sensation with higher UTCI equivalent temperature limits than those categorized in terms of thermal stress. The upper limits for thermal comfort zone indicate that Tropical populations are adapted to heat stress conditions, as expected.

In the case of cold TSV limits, no correspondence between the local thermal sensation classes derived from the field surveys were observed between Tropical and other climates (Table 1). In regarding to Continental Temperate climate, it should be noted that this slightly cold stress range is within the thermal neutrality range for Chinese populations (Lai et al. 2014) and reveals that Tropical climate populations present low resilience to cold stress conditions. In fact, the range is closer to that determined for Mediterranean climate (Pantavou et al. 2013). Rossi et al. (2012) was not able to define this range for Subtropical climate in the south of Brazil. In the current research, only upper limit of moderate cold thermal sensation was defined for UTCI temperatures (14.5 °C) due to the environmental conditions under which the campaigns were conducted, which is very close to that determined by Pantavou et al. (2013). In the case of hot thermal sensation classes, the lower and upper limits were displaced upward by at least 3 °C in relation to the Continental Temperate climate and more than 4 °C when compared with Mediterranean climate. Rossi et al. (2012) was not able to define this range for Subtropical climate in the south of Brazil, only the lower limit (27 °C). This demonstrates that populations are well acclimatized to heat stress conditions, while those living in European cities, south Brazil, and China must adapt to higher thermal variability caused by the presence of well-defined seasons throughout the year.

The derivation of a local thermal sensation scales for UTCI is important since it can be applied in urban planning or when designing or re-qualifying outdoor spaces, helping to enhance the quality of urban environments. In the study region, the estimated UTCI limits based on votes revealed the resiliency of the local population to higher warmer UTCI temperatures and lack of acclimatization and adaptation to colder temperatures when compared with similar studies conducted in other climates.

Analyzing the local thermal sensation vote by gender, the comfort zone for female group (24–28 °C) was narrower than the male group (20–28.5 °C), demonstrating the lower acceptability capacity of the former to thermal conditions. This was also reported by Huang et al. (2016) in a Humid Temperate climate, where the neutral zone amplitude for females (14.6–27.8 °C) and males (16.5–29.1 °C) were different and more flexible than those observed in Tropical climate, as a consequences of population exposure to significant weather variety conditions and, consequently, inducing acclimatization to both heat and cold conditions. Neutral temperatures were also higher than those reported in Wuhan (China-Cfa), where neutral temperatures for men and women were calculated at 21.2 and 22.8 °C, respectively. The difference in acclimatization by gender reveals the need for different thermal environmental conditions to maintain group neutrality.

When relating thermal sensation by gender to thermal insulation derived from the field, the linear regressions equations indicated that both groups present the same thermal sensation at 28 °C UTCI. Above this reference value, the male population feels less heat than the female one. Below this value, males feel less cold. This aids in the understanding of the clothing insulation model generated by gender, shown in Fig. 1 b, where the female group required higher thermal insulation than the male group for temperatures below 30 °C, since females felt colder below 28 °C (Fig. 3b). Thus, strategies to promote adequate urban thermal conditions should take into account the fact the different comfort zones between males and females. These results corroborate the sensitivity differences between genders pointed out by Krüger, Givoni, and Rossi (2010) and Karjalainen (2007).

The impact of using artificial air conditioning is confirmed by the reduction of the neutral temperature between the assessed groups (24.2 °C for AC users; 25 °C for NAC users). Acclimatization to air conditioning is more significant at high heat stress temperatures (Fig. 3c), whereas the effect tends to degenerate between groups in the case of cold stress conditions. This may be underscored by calculating the upper and lower limits of the comfort zone, of (+ 0.5) and (− 0.5) for NAC and AC groups, respectively. For the upper limit, the neutral temperature is reduced from 28.50 to 27.50 °C. In turn, for the lower limit, it decreases from 21.4 to 21 °C. Therefore, the acclimatization effect tends to disappear as temperatures decrease, but intensifies as temperatures increase, influencing upper heat of TSV classes. This behavior was not verified by Krüger, Drach, and Bröde (2015) since the fitted curves derived for AC users and NAC users presented angular coefficients very close to each other.

Due to the observed behavior, people who do not use air conditioning are more tolerant to outdoor heat stress than those who frequently remain in air-conditioned environments. In Singapore (Yang et al. 2013), the reduction in neutral temperature amounted to 0.5 °C between the group working in air-conditioned environments and those who appreciate naturally ventilated environments. In Rio de Janeiro, Brazil, the decrease was more significant, from 24.5 °C (NAC) to 21.70 °C (AC) by the UTCI scale (Krüger, Drach, and Bröde 2015). This may be attributed to the fact that AC users remain in more stable and cooler environments than those in naturally ventilated places or in open spaces, where physiological and psychological adaptations are constantly required.

The percentage of dissatisfied people (PD) amounted to 6.32%, slightly higher than the minimum percentage of 5% established by Fanger (1972) for indoors spaces. However, it was lower than the percentage reported for Subtropical and Mediterranean climates, with a minimum percentage of 10% (Rossi et al. 2012; Pantavou et al. 2013). Since the curve displays an eccentricity to the right (inflection point of 0.061), it reflects resident adaptability to accept warmer thermal environments as a result of the tolerance responses observed in comfort and slightly warm environmental conditions. This acceptance/preference confirms the population’s climate adaptability and indicates respondent resilience to heat stress conditions. The higher percentage of people dissatisfied in open areas compared with indoor spaces is a consequence of the significant environmental condition variability experienced in urban environments.

In the case of temperatures within the thermal comfort zone (− 0.5 < TSV < + 0.5), the percentage of dissatisfied people in the Tropical climate reached ~ 7%, lower than that predicted by the Fanger’s model in a climatic chamber (10%) and attending ASHRAE 55 (2004), at 93% thermal acceptability. Furthermore, in the case of Subtropical and Mediterranean regions, the percentage of dissatisfied people was higher than that reported for Tropical climates (of 15 and 13%, respectively), indicating that urbanites are well acclimatized to the climate of the researched area. In addition, it should be underscored that second-order polynomial equation terms for Subtropical and Mediterranean climates were different from those found for Tropical climates (see data in Online Resource 7). This suggests that these populations display different thermal adaptations, with their own thermal tolerance levels for cold and heat conditions, as stated previously.

Conclusion

This study discusses findings concerning outdoor thermal sensations obtained in Cuiabá, located in the Brazilian Midwest, a Tropical Savannah Climate region. Thermal indices provide a measure of thermophysiological reactions of human organisms and the thermal sensation comprises a complex interaction between several factors, such as thermal environment conditions, thermal exposure history, acclimatization, geographical position, and cultural and sociological perceptions,. The differences between local thermal sensation scales for UTCI obtained on surveys conducted in other climates and those resulting from thermal sensation votes declared by Savannah residents were identified. Based on the clothing thermal insulation and thermal sensation vote analysis declared by the groups and subgroups researched, the conclusions of this study are as follows:

i. The local thermal comfort zone (between 21.5 and 28.5 °C) is more restrictive and displaced upwards in relation to those established for European and Chinese populations;
ii. Slightly cold and cold TSV categories are within the thermal neutrality limits for Continental Temperate and Mediterranean climate populations, revealing lack of urbanite acclimatization to cold stress conditions;
iii. Residents are well acclimated to heat stress conditions, with the local TSV heat limit classes established by the regression analysis displaced at least 3 °C above the original classes proposed for Europeans and other populations;
iv. Clothing thermal insulation (Icl) required by the residents during the campaigns on cold days was lower than that predicted by the intrinsic UTCI clothing model. This was attributed to the lack of adequate winter clothes, as well as the relatively low frequency of cold days, where people receive cold days as a relief from the constant heat stress conditions inherent to the region. For future studies, interviewees may have the opportunity to choose their clothing isolation to verify whether or not they accept more thermal insulation on cold days;
v. The female population is more sensitive to cold thermal environments, since their lower thermal comfort zone limit is higher compared with males, but also because they demand more thermal clothing insulation below 28 °C than males; and,
vi. Gradual physiological adaptation to the use of artificial air conditioning system by continuous exposure was confirmed in the study region. The neutral temperature of people who use artificial air conditioning (24.2 °C) was lower than non-users (25 °C). Differences between these groups are higher in hot stress ranges, while tending towards a decrease in the cold.

Since thermal comfort plays an important role in the use of urban outdoor spaces, especially in Tropical climates, in order to make them attractive, urban planning strategies should take into account thermal sensation differences between the researched groups when designing or re-qualifying outdoor spaces. Thus, an adequate local thermal sensation evaluation becomes an important tool to subsidy improvements to city dweller living conditions.

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