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Application of selected indices on outdoor thermal comfort assessment in Midwest Brazil

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Abstract

This paper presents the results of outdoor thermal comfort research conducted in a public square of Campo Grande (hot-humid climate) during hot and cold seasons. The objective is to compare the predictive ability of the following indices: Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), Perceived Equivalent Temperature (TEP), Sense of Thermal Comfort (Y_{DS}), and Predicted Mean Vote (PMV). To obtain necessary data, micrometeorological measurements and questionnaire surveys were performed simultaneously during field campaigns. We found that a purely physiological approach was insufficient in the assessment, as the selected indices did not efficiently predict the thermal sensation votes of the locals. PET and UTCI had relatively satisfactory performances, but regional calibration was necessary. Acquired subjective votes enabled the proposal of PET calibration (comfort range 21-27 °C PET). Based on the adjusted thermal scale (63% accuracy), discomfort hours were estimated. Results provided by this study can help landscape architects and urban planners define specific design guidelines for urban open spaces of Campo Grande.

Keywords: Predictive ability; Thermal index; PET calibration; Field experiment; Hot-humid climate.

1. Introduction

Cities are complex networks of interconnected systems, in such a way that changes in the built environment directly affect its microclimate. In turn, changes in the microclimate affect the local environmental quality, which result in (often negative) effects on the health and comfort of urban dwellers [1, 2, 3]. Furthermore, microclimate modifications can increase energy consumption of buildings for cooling purposes [4, 5].

By remodeling the physical attributes of the urban space, its thermal conditions can be improved, which positively influence the use of outdoor areas [6, 7]. Therefore, it should be encouraged the application of bioclimatic principles in landscape architecture and urban planning. There is today a wide range of indices which estimate and quantitatively express the thermal comfort level of people. Based on the heat balance between the body and the environment that surrounds it, these predictive models are helpful tools in the designing process as they straightforwardly assess the thermal environment.

Some indices extensively applied in the urban outdoor context are the Physiological Equivalent Temperature (PET) [8], Universal Thermal Climate Index (UTCI) [9] and Predicted Mean Vote (PMV)

[10, 11]. Some indices developed to be applied in specific contexts include the Outdoor Standard Effective Temperature (OUT_SET*) [12] (Australia), the Actual Sensation Vote (ASV) [13] (Europe), Perceived Equivalent Temperature (TEP) [14] (Brazil/subtropical), Sense of Thermal Comfort (Y_{DS}) [15] (Indonesia/humid-tropical), among others.
It is the objective of this study to compare the predictive ability of selected methodologies. It was done so by obtaining actual sensation votes (Thermal Sensation Vote, TSV [16]) and comparing it with calculated votes (PMV, PET, UTCI, Y_{DS}, and TEP). Data were collected in a public square located in Campo Grande, of hot-humid climate, during spring and winter. The indices were selected based on the assumption that they could be suitable to the climatic characteristics of the studied area. The acquisition of local subjective votes also enabled the proposal of PET calibration to the physiological reality of Campo Grande inhabitants.

2. Materials and methods

2.1 Study area

Campo Grande (20º28'13" S, 54º37'25" W, 600m), capital of Mato Grosso do Sul state, is a city of approximately 800.000 inhabitants in Midwest Brazil. It is found in a transitional zone between humid subtropical (Cfa) and tropical wet and dry (Aw) climates under Köppen-Geiger classification [17] (Figure 1). Mean air temperatures recorded during spring (September to December) and summer (December to March) are fairly similar (Figure 2). Therefore, spring months can well represent the local hot season. Such data were obtained from Energy Plus weather file (EPW) format, downloaded from the U.S. Department of Energy website (historical series 1973-1991). The field experiment was conducted in a centrally-located public square (approximate area of 14400 m^2), selected due to its high density of usage and relevant historical importance to the city (Figure 3).

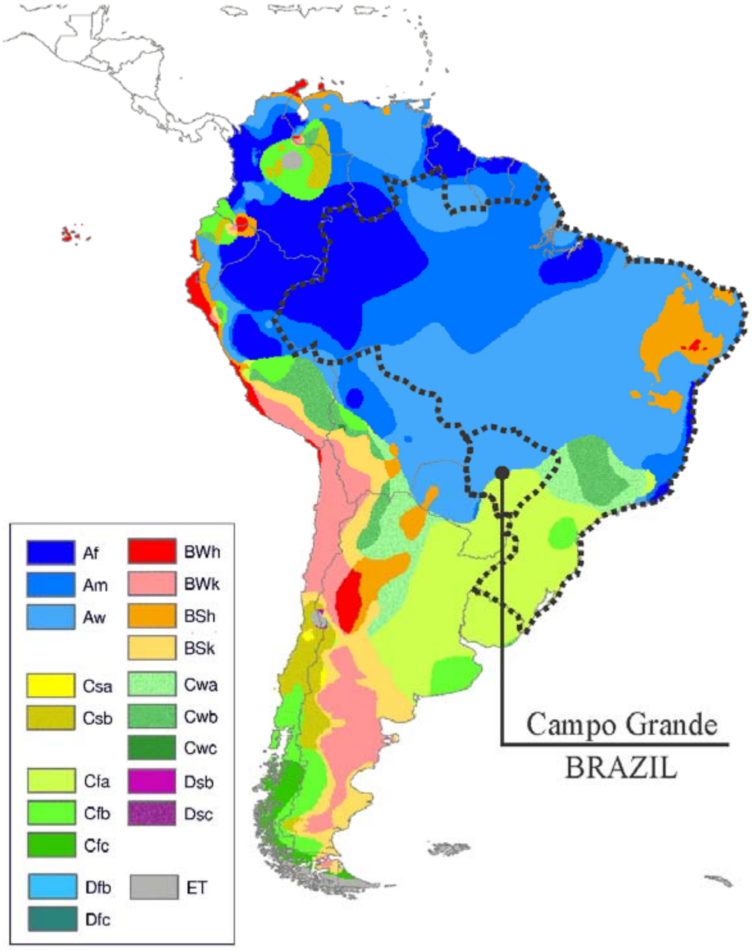

Figure 1. Climatic classification of South America (Brazil highlighted). Adapted from Peel et al. (2007).

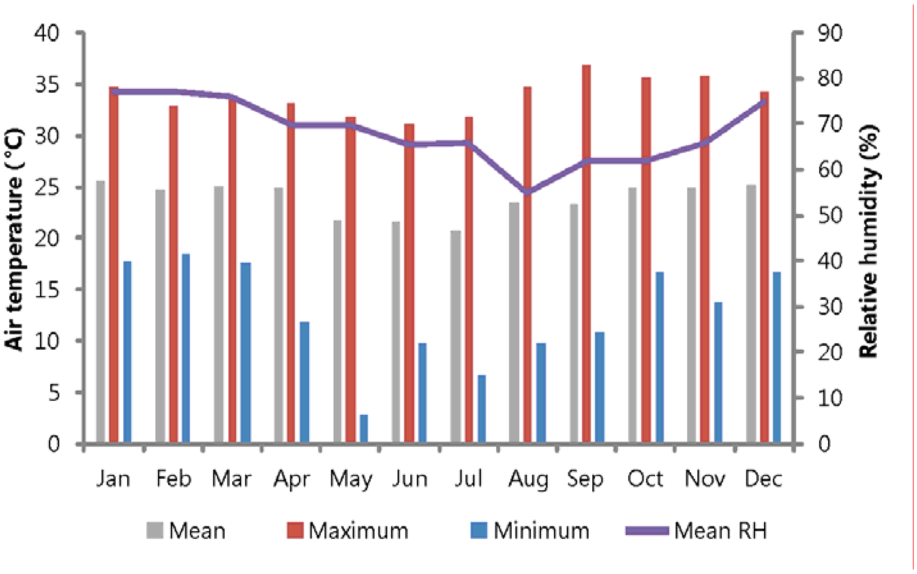

Figure 2. Air temperature and relative humidity in Campo Grande (historical series 1973-1991).

Figure 3. Public square where data were collected.

2.2 Data collection

For data collection, micrometeorological monitoring and questionnaire surveys were conducted simultaneously. The field research occurred in winter (July 2015) and spring (November 2015), comprising a total of four days of measurements and 428 thermal comfort questionnaires (of which 408 were valid).

2.2.1 Micrometeorological monitoring

In order to calculate the indices, the following microclimatic variables were obtained: air temperature (ºC), relative humidity (%), mean radiant temperature (ºC) and air velocity (m/s). A calibrated portable weather station BABUC/A was used; its components (Table 1) were mounted on an adjustable tripod at 1.1 meter. All data collected were processed through InfoGAP software, mean radiant temperature was estimated using RayMan v. 1.2 model. Monitoring was performed in accordance to the recommendations of accuracy of ISO 7726 [18]. Such Standard does not provide specific guidelines for outdoor spaces, but many similar studies have effectively used it [7, 14, 19, 20].

2.2.2 Questionnaire surveys

Thermal comfort questionnaires were applied randomly to people in a relaxed state present in the square. Individuals were enquired about their personal information, such as age, height, weight, gender, clothing insulation, and metabolic rate (which is related to the degree of activity of the body). Both clothing insulation and metabolic rate values were estimated in accordance with [11].

Thermal sensation votes were acquired through a subjective judgment scale, which was elaborated according to [16]. The scale has a symmetrical structure of two poles (positive and negative), with seven degrees of intensity (ranging from -3, "very cold", to +3, "very hot"), with a central point of indifference (zero, "neutral"). It is preceded by the question "how are you feeling right now?".

Table 1. Technical characteristics of the sensors.

Component	Measured parameters	Measuring range	Accuracy/ precision	Response time (T90)
Psychrometer (BSU102)	Dry and wet ventilated temperature, Relative Humidity	Dry temp.: -25 to +150°C Wet temp.: 0 to +60°C RH: 0 to 100%	RH: 70 to 98%: 0,5% 40 to 70%: 1% 15 to 40%: 2%	90 sec with fan operating
Hot wire anemometer (BSU101)	Air velocity	0 to 50 m/s	±4 cm/sec 4% > 1m/s	10 ms
Natural ventilation wet bulb temperature probe (BSU121)	Wet bulb temperature	0 to +60°C	Pt100 1/2 DIN (±0.15°C at 0°C)	6 min.
Radiant temperature sensor (BST131)	Radiant temperature	-10 to +100°C	1/2 DIN (±0.15°C at 0°C)	20 min.

3. Theory and calculation

The most widely used thermal index is Predicted Mean Vote (PMV), developed by Fanger [10]. Originally developed as an indoor thermal comfort index, PMV has also been commonly adopted in outdoor thermal comfort studies, even though many researches have reported inaccuracy when it is applied in more dynamic environments [21, 22]. PMV provides an average value of thermal sensation votes from a large group of people based on six variables: metabolic rate (*met*), clothing insulation (*clo)*, air temperature (°C), mean radiant temperature (°C), air velocity (m/s) and relative humidity (%). Its value is expressed in a seven-point scale, ranging from "very cold" (-3) to "very hot" (+3). PMV is included in ISO 7730 [23], the first thermal comfort Standard to be used in global scale.

Physiological Equivalent Temperature (PET) [8] derived from Energy Balance Model for Individual (MEMI) and it is recommended by the German Association of Engineers (VDI-Guideline 3787). As it is expressed in degrees Celsius (°C), PET is of easy and immediate interpretation. The index is defined as "the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed" [24]. It is calculated based on climatic variables: air temperature (°C), mean radiant temperature (°C), air velocity (m/s) and relative humidity (%) (or vapour pressure). The importance of PET in the assessment of outdoor thermal comfort conditions is recognized, and its accuracy has been confirmed by several studies [3, 6, 22, 25].

Both PMV and PET were calculated simultaneously using RayMan v.1.2 model [26, 27]. RayMan's applicability in complex urban environments has been confirmed by many studies [25, 28, 29]. Whilst PMV and PET require climate variables to be measured at 1.1 meter, which is the average height of the centre of gravity in adults [8], UTCI method requires wind speed to be measured at 10 meters above surface. For this reason, Hellman's exponential law (1) [30] was used to recalculate wind speed.

$$\frac{V}{V_{10}} = \left(\frac{H}{H_{10}}\right)^{\alpha} \tag{1}$$

where V is wind speed at 1.1 meter (m/s), V_{10} is wind speed at 10 meters (m/s); H is height of 1.1 (m); H_{10} is height of 10 (m), α is the friction coefficient ($\alpha = 0.40$ for urban areas).

In 2002, the International Society of Biometeorology (ISB) established Commission 6 on the development of a Universal Thermal Climate Index (UTCI), aiming to create an international standard based on the latest scientific progress in thermo-physiological modeling [31]. UTCI is defined as an equivalent temperature for a person walking at 4 km/h, with adapted clothes, in outdoor conditions of 50% relative humidity, still air, and mean radiant temperature equal air temperature [31]. The index assesses outdoor thermal conditions in the major fields of human biometeorology, considering the interaction between air temperature, wind speed, air humidity, and long-wave and short-wave radiant heat fluxes [7].

Sangkertadi and Syafriny [15] proposed equations to assess outdoor thermal comfort conditions in humid-tropical regions based on field data collected in Indonesia. Three regression equations were developed to represent three modes of activity: normal walking (speed of about 2 km/h), brisk walking (speed of about 4-5 km/h) and seated people performing moderate activity. Only the latter was used (2).

$$Y_{DS} = -7.91 - 0.52v + 0.05T_a + 0.17T_g - 0.0007RH + 1.43Adu \tag{2}$$

where v is air velocity (m/s), T_a is air temperature (°C), T_g is globe temperature (°C), RH is relative humidity (%), Adu is area of body skin surface DuBois (m^2).

Area of body skin surface [32] is given by Equation (3):

$$Adu = 0.202 * H^{0.725} * W^{0.425} \tag{3}$$

where H is height (m) and W is weight (kg).

Monteiro and Alucci [14] proposed regression equations to assess outdoor thermal comfort conditions in urban areas based on field data collected in São Paulo, Brazil. Perceived Equivalent Temperature (TEP) is defined as an equivalent temperature for a person with adapted clothes, standing still, in outdoor conditions of 50% relative humidity, still air (air velocity of 0.1 m/s), and mean radiant temperature equal air temperature. It is given by Equation (4):

$$TEP = -3.777 + 0.4828T_a + 0.5172T_{mr} + 0.0802RH - 2.322V_a \tag{4}$$

where T_a is air temperature (°C), T_{mr} is mean radiant temperature (°C), RH is relative humidity and V_a is air velocity (m/s).

4. Results and discussion

Considering 853.622 as population size (estimated number of Campo Grande inhabitants in 2015, according to the Brazilian Institute of Geography and Statistics [33]), a minimum of 400 questionnaires is required (5% sampling error). The sample size equation proposed in [34] was used. Since 408 questionnaires is considered as an acceptable sample size, the results can well represent the population of Campo Grande. Questionnaires have a good balance of gender (45% men and 55% women) and distribution among seasons (50% winter and 50% spring). The results of the micrometeorological monitoring are presented in Table 2.

Table 2. Microclimatic variables monitored during the questionnaire surveys.

	Air temperature (°C)		Mean radiant temperature (°C)		Relative humidity (%)		Air speed at 1.1 meter (m/s)	
	Winter	Spring	Winter	Spring	Winter	Spring	Winter	Spring
Minimum	15.3	29.2	17.5	29.4	42.6	44.6	0.3	0.1
Mean	20.4	30.7	23.4	32.1	53.8	54.3	2.1	1.4
Maximum	25.4	32.3	29.9	33.6	68.2	63.5	5.1	5.5

Since thermal sensation votes were directly stated by people, they were considered in this study as the actual votes. Therefore, each calculated index had their results compared to TSV's. However, only TEP and PMV had their interpretative ranges based on a seven-point scale, such as TSV's. For this reason, PET, UTCI, and Y_{DS} scales were adapted for equivalent representation (Table 3).

4.1 Predictive Mean Vote (PMV)

PMV had a predictive ability of 19%. Of all analyzed indices, it had the lowest performance which can be justified by many reasons. PMV was developed for indoor thermal comfort assessment and therefore has limited application due to the narrow air temperature (10 to 30 °C) and wind speed (up to 1.0 m/s) ranges it supports [11]. It overestimated cold discomfort mainly because air velocity monitored often exceeded 1 m/s (what could be expected of open spaces). Indeed, PMV often overestimates heat discomfort in hot climates and cold discomfort in cold climates [22]. Another important limitation of PMV is that it is based on the steady-state energy model. The steady-state model is based on the assumption that "people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium" [36]. However, people rarely reach thermal equilibrium in open areas [37].

Table 3. Adapted thermal comfort interpretative ranges.

Sensation	TSV	PMV	PET (°C)	UTCI (°C)	Y_{DS}	TEP
Very cold	-3	-3	< 4	< -13	≤ -3	-3
Cold	-2	-2	4 to 8	0 to -13	-2	-2
Slightly cold	-1	-1	8 to 18	+9 to 0	-1	-1
Neutral	0	0	18 to 23	+9 to +26	0	0
Slightly hot	+1	+1	23 to 35	+26 to +32	+1	+1
Hot	+2	+2	35 to 41	+32 to +38	+2	+2
Very hot	+3	+3	> 41	> 38	+3/ +4/ +5	+3
References/ Adapted from	[16]	[11]	[35]	[9]	[15]	[14]

4.2 Physiological Equivalent Temperature (PET)

PET is also based on the steady-state model, hence being limited by such an approach. However, the index has been applied successfully in several outdoor thermal comfort studies at different climatic contexts [3, 22, 25, 28, 29]. PET, in this study, was interpreted using the scale proposed in [35], obtained in Central Western Europe. The predictive ability of PET was 44%, the best performance among the selected indices.

4.3 Universal Thermal Climate Index (UTCI)

We applied a simplified calculation of UTCI by inserting required climatic data into UTCI calculator [9]. In this simplified method, clothing insulation is set as constant based on European clothing adaptation habits, which could not well reflect local habits. A more accurate predictive method would be obtaining UTCI equivalent temperatures by running UTCI-Fiala model coupled with a clothing model [7]. UTCI is valid in all climates, seasons and scales and it is independent of the individual's characteristics [31]. But regional calibration might be necessary for different seasons and climate zones [38]. It overestimated comfort mainly due to its large comfort range of 17 degrees (+9 to +26). As the model assumes the individual is walking at 4 km/h, the index might be more suitable for studies assessing passers-by and not people at rest (at least when the simplified method is applied). Despite the limitations of such an approach, UTCI's predictive ability was relatively satisfactory (43%). PET and UTCI had similar performances, as also found in [39].

4.4 Sense of Thermal Comfort (Y_{DS})

Y_{DS} overestimated cold discomfort, and had a predictive ability of 38%. The equation only includes the personal variables weight and height (incorporated in the DuBois body skin surface variable), and does not take in consideration clothing insulation. Indeed, during hot seasons, people typically dress minimally hence clothing insulation is fairly standardized and could be set as constant. However, during cold seasons, clothing adjustment gains more importance as an adaptive strategy [28]. The fact that it was not included in the equation could partially explain why the index could not more accurately predict sensation votes in this study, especially during the cold season.

4.5 Perceived Equivalent Temperature (TEP)

TEP had a predictive ability of 34%. In 8% of the individual votes obtained, wind speed exceeded the maximum value the methodology supports (3.6 m/s). This could partially explain why TEP underestimated heat discomfort. The authors say that the application of such methodology in different contexts from which it was created depends on the verification of correlation between observed and hypothetical data [14]. Indeed, São Paulo (where data used as base to develop the index were collected) is classified as of warm temperate climate (Cwa [17]), a different climate from Campo Grande's. Therefore, as the authors say, regional calibration is necessary for more accurate results.

4.6 Regional calibration of PET

Results indicate that the selected indices did not efficiently predict the sensation votes of the locals (all under 50% accuracy). In a similar study conducted in Argentina (arid climate) [20], the predictive ability of PMV and PET did not even exceed 25%. Given the limitation of the performances, regional calibration was necessary. PET was the index chosen to be calibrated because many outdoor thermal comfort studies around the world have successfully applied it, which would allow a comparison of this study with results found in different contexts. Calibration was performed using subjective votes obtained during the field campaigns. These were distributed as a function of PET ranges (Figure 4). The hypothesis of normality was rejected for both PET and TSV results (applying the Kolmogorov-Smirnov test). However, they were considered as normally distributed since these are large sample sizes ($n=408$). With large sample sizes ($n > 30$), the assumption of normality should not cause major problems [40].

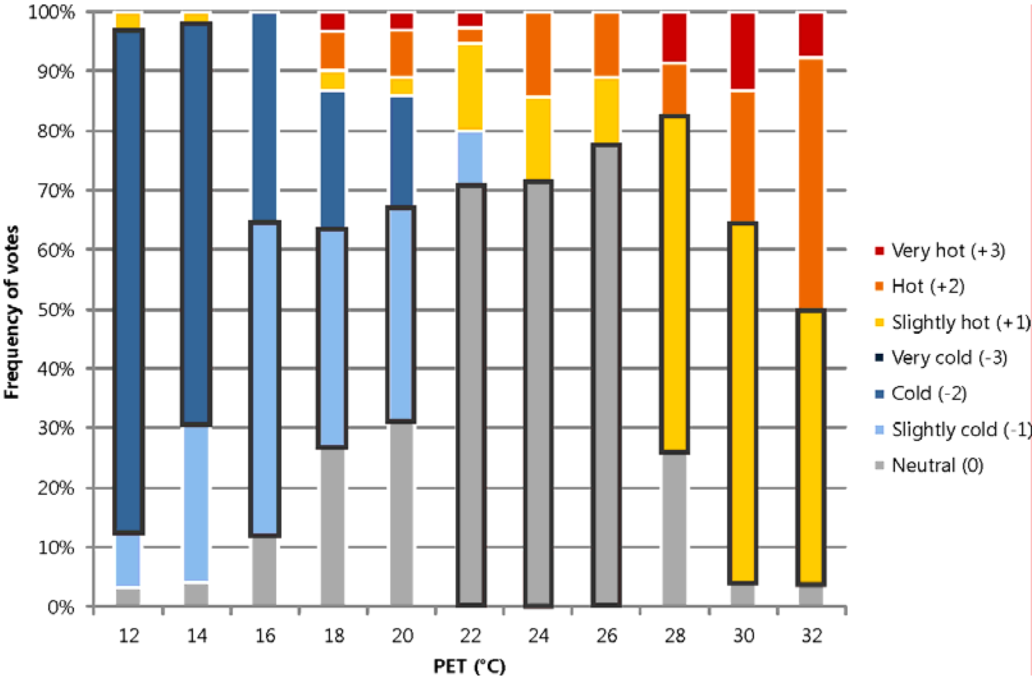

Figure 4. Frequency of TSVs as a function of PET ranges.

The calibrated interpretative scale of PET was organized by observed predominance of votes (Table 4). The maximum PET value obtained was 33 °C, therefore, "hot" and "very hot" ranges could not be accurately determined. The comparison of the results with previous similar studies reveal that thermal comfort ranges indeed vary according to different climatic contexts, reaffirming the results found in [20, 29, 41, 42]. This can be mainly explained by regional acclimatization (physiological thermal adaptation) [43].

Table 4. Comparison between PET-Campo Grande interpretative thermal range and others.

Sensation	PET-Central Europe (°C)	PET-Taiwan (°C)	PET-Vitória/Brazil (°C)	PET-Campo Grande/ Brazil (°C)
Very cold	$PET \leq 4$	$PET \leq 14$	-	$PET \leq 11$
Cold	$4 < PET \leq 8$	$14 < PET \leq 18$	$18 < PET \leq 20$	$11 < PET \leq 15$
Cool	$8 < PET \leq 13$	$18 < PET \leq 22$	-	-
Slightly cool	$13 < PET \leq 18$	$22 < PET \leq 26$	$20 < PET \leq 22$	$15 < PET \leq 21$
Neutral	$18 < PET \leq 23$	$26 < PET \leq 30$	$22 < PET \leq 30$	$21 < PET \leq 27$
Slightly warm	$23 < PET \leq 29$	$30 < PET \leq 34$	$30 < PET \leq 34$	$27 < PET \leq 32$
Warm	$29 < PET \leq 35$	$34 < PET \leq 38$	-	-
Hot	$35 < PET \leq 41$	$38 < PET \leq 42$	$34 < PET \leq 46$	$PET > 32$
Very hot	$PET > 41$	$PET > 42$	$PET > 46$	-
References	[35]	[41]	[29]	This study

PET-Campo Grande could accurately predict 63% of TSVs. The predictive ability of the indices was verified by comparing actual and predicted votes individually. Figure 5 shows the frequency of the votes according to each methodology. Indices such as PET and TEP have similar frequency but different distribution of votes, which reflected on their different accuracy rates.

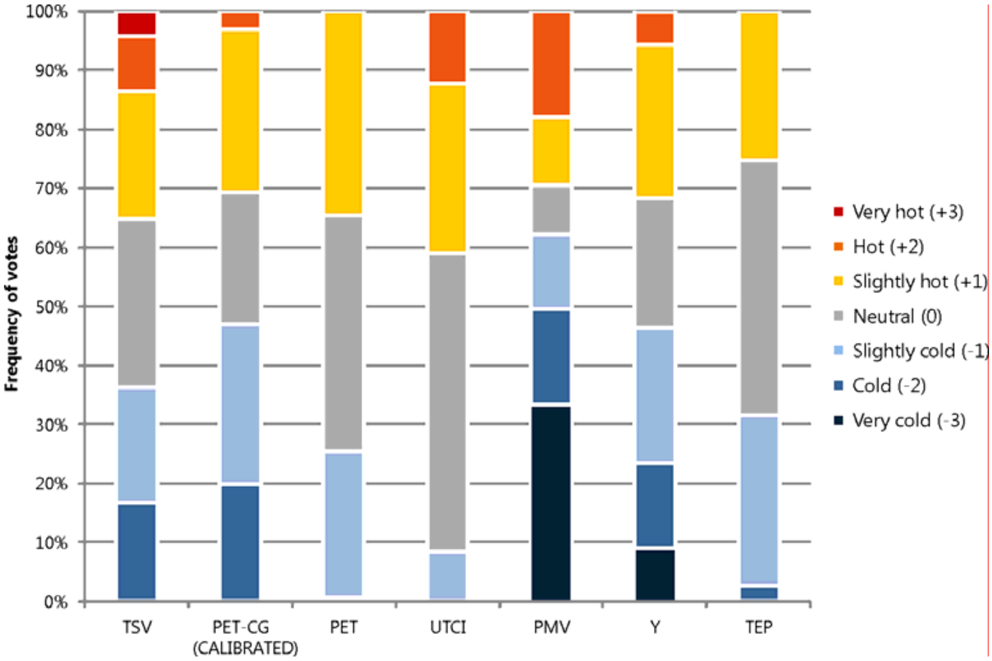

Figure 5. Frequency of actual and predicted sensation votes.

Mean PET values were calculated hourly for July and November, based on climatic variables obtained from the EnergyPlus weather file. Clothing insulation and metabolic rate were set as constant based on the mean values obtained during the field campaigns: for winter, 0.6 *clo* and 68 W, respectively; for spring, 0.5 *clo* and 67 W, respectively. According to [44], a thermal condition can be considered "acceptable" when TSVs are "slightly hot" (+1), "comfortable" (0) or "slightly cold" (-1). Thus, these votes were grouped in a central "no thermal stress" zone. Applying the adjusted interpretative scale, discomfort hours were estimated for both hot and cold months (Figure 6). Thus, during November (spring), heat discomfort hours last from 9:30 until 15:30. During July (winter), cold discomfort hours last from 17:30 until 07:30.

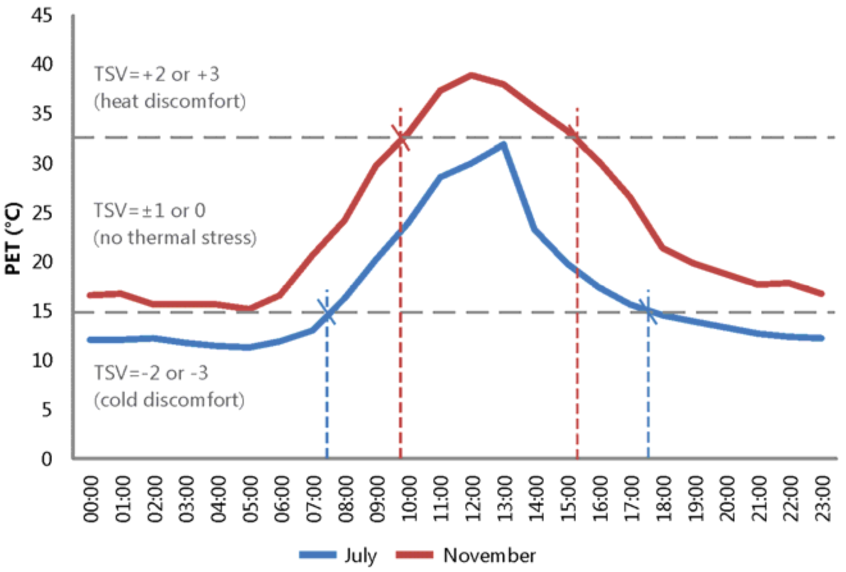

Figure 6. Discomfort hours during the studied months, according to the calibrated scale.

5. Conclusions

We found that, even though microclimatic conditions greatly influence the individual's perception of the thermal environment, a purely physiological approach is insufficient in the assessment of outdoor thermal comfort conditions. This was evidenced by the predictive ability of the selected indices (all under 50% accuracy), which did not efficiently predict the thermal sensation votes of the locals. PMV was considered not suitable to outdoor assessment, mainly due to its excessive sensitivity to air speed variations (particularly its cooling effect). TEP and Y_{DS} were developed to be applied in specific climatic contexts, hence limitations were observed due to local thermal adaptation. PET and UTCI had relatively satisfactory performances, but regional calibration was necessary. PET calibration for Campo Grande was then proposed based on subjective votes acquired during field campaigns. The comfort range obtained was 21-27 °C PET. The adjusted interpretative scale had a predictive ability of 63%. The obtained thermal ranges were compared to those found in studies conducted in different geographic and climatic contexts. The results reaffirm that thermal sensations vary around the world, suggesting the influence of regional acclimatization. Based on the adjusted thermal scale, discomfort hours could be easily predicted. Such information can help landscape architects and urban planners define specific design guidelines for urban open spaces of Campo Grande, encouraging their use throughout the day and seasons.

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