

Designing Thermally Pleasant Open Areas: The Influence of Microclimatic Conditions on Comfort and Adaptation in Midwest Brazil

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Abstract

The increasing temperatures in urban areas can negatively affect the health and comfort of its dwellers. Thus, this study assessed thermal comfort conditions in a public square, located in hot-humid Midwest Brazil, based on the relationship between microclimate conditions, thermal sensations and adaptation. Data used were collected through micrometeorological measurements and questionnaire surveys, which were performed simultaneously in field campaigns during hot and cold seasons. The aim was to propose design guidelines for open areas according to local thermal preferences. An updated regionally-calibrated Physiological Equivalent Temperature (PET) assessment scale is also proposed. Neutral temperatures were estimated on a seasonal basis and critical discomfort hours on a monthly basis. The results reaffirm that psychological and behavioral factors influence the individuals' assessment of the outdoor thermal environment and therefore should be considered as design criteria. To improve the microclimate of urban open areas in Campo Grande, shading must be provided primarily by trees and resting areas should be protected from wind exposure. The use of water features for evaporative cooling purposes is not recommended, however, drinking fountains should be available in public squares. Such results can be used by landscape architects and urban planners to deliver thermally comfortable open spaces, encouraging greater use and increased length of stay in these areas.

Keywords: field experiment, outdoor thermal comfort, hot-humid climate, Physiological Equivalent Temperature (PET), landscape architecture

1. Introduction

Mean annual temperatures in cities are expected to increase by up to 4.9 °C by the 2080s as a consequence of climate change and the urban heat island effect (UCCRN, 2015). Due to dramatic projections as this, climate resilience has become an environmental priority towards sustainable development all over the world. Given the potentially harmful impacts of high temperatures on the comfort of city inhabitants, urban heating mitigation must be made a priority by planning authorities (Ketterer & Matzarakis, 2014) by means of conscientious design. Environmental conditions in cities can be improved by appropriate arrangement of urban elements, as they determine sun and wind exposure directly impacting the local microclimate (Thorsson et al., 2011).

The increasing temperature of cities is a particularly relevant issue in tropical countries, such as Brazil. Recent Brazilian studies have assessed outdoor thermal comfort conditions with focus on physical attributes of the city, such as: urban geometry (Krüger et al., 2011), Sky View Factor (Minella et al., 2011), ventilation (Silva & Alvarez, 2015), vegetation (Abreu-Harbich et al., 2015), surface properties and land use (Carfan et al., 2014). Thus, a study more focused on psychological factors can be of significant contribution to better practices of climate-sensitive design in Brazil.

The conventional concept of thermal comfort involves physical and physiological aspects, thus most studies are based on theoretical thermoregulatory models (Nikolopoulou, 2011). But studies conducted in Europe (temperate climate predominantly) (Nikolopoulou et al., 2001; Nikolopoulou & Steemers, 2003; Thorsson et al., 2004) and

Taiwan (hot-humid climate) (Lin, 2009; Lin et al., 2013) have demonstrated that psychological and behavioral thermal adaptation play an important role on the individual's perception of the outdoor thermal conditions. Therefore, it is not enough to design open spaces based on the physical environment only (Nikolopoulou & Steemers, 2003).

From the physiological point-of-view (objective), the relationship between microclimate conditions and human thermal comfort was assessed in this study using Physiological Equivalent Temperature (PET) (Höppe, 1999). PET is a thermal index extensively applied in urban outdoor studies. It is calculated based on four climatic variables (mean radiant temperature, air temperature, air velocity and relative humidity) and two personal variables (clothing insulation and metabolic rate). From the psychological point-of-view (subjective), the relationship between microclimate conditions and human thermal comfort was assessed based on the factors proposed in Nikolopoulou and Steemers (2003). According to the authors, the adaptive opportunity (the degree of which people can adapt to the environment) can be separated into three main categories: physical (reactive and interactive), physiological (or acclimatization) and psychological (naturalness, past experience, perceived control, time of exposure, environmental stimulation and expectations). In this study, such psychological adaptation factors are addressed individually and related to both microclimate conditions and thermal sensations.

The aim of this study is to propose design guidelines for open areas in the city of Campo Grande (Midwest Brazil) based on local psychological and physiological thermal preferences. It was done so by evaluating the relationship between microclimate conditions, thermal sensations and adaptation. Data used were collected through micrometeorological measurements and questionnaire surveys, which were performed in field campaigns during cold and hot seasons. Climate adaptation is a relatively new field thus knowledge is still scarce and fragmented (UNISDR, 2012). Therefore, the proposal of design measures to improve environmental conditions in cities is of urgent importance, as climate change will inevitably increase the susceptibility of urban societies if effective adaptations do not take place soon (UNHABITAT, 2011). The application of bioclimatic concepts in landscape architecture contributes to deliver environments which are thermally suitable according to local preferences, encouraging greater use and increased length of stay in outdoor spaces.

2. Method

2.1 Study Area

Campo Grande (20°28'13" S, 54°37'25" W, 600m elevation) is the capital of Mato Grosso do Sul state, located in Midwest Brazil (Figure 1). It is situated between Paraná and Paraguai, the two largest rivers in the region and about 400 km away from Pantanal, the biggest wetland area in the world (an UNESCO World Heritage Site). The estimated population size of Campo Grande in 2015 was 853.622 inhabitants (IBGE, 2010). The local climate is characterized by extended hot season and it can be described as Temperate hot summer without dry seasons (Cfa), borderline Tropical Savannah zone (Aw), under Köppen-Geiger classification (Peel et al., 2007). The mean air temperature in Campo Grande in Summer is 25.2 °C, 25.1 °C in Spring and 22.3 °C in Winter (2008-2015) (CEMTEC, 2016).



Figure 1. Location of Campo Grande city in Brazil

The focus of this study is Ary Coelho Square (Figure 2), which was selected as study area due to its high density of usage, being inserted in a predominantly commercial district located right in the city center. It also has

relevant cultural and historical importance as it was the first public open space in the city, inaugurated in 1909. The square went through revitalization in 2011, as the municipality aims to preserve local architectural heritage and improve the environmental quality of the city center. Its surroundings consist mainly of one to two-storey commercial buildings and streets with high levels of traffic (Figure 3). Ary Coelho comprises a total area of 14.400 m² and approximately 30% of its surface is vegetation. Shading density varies along the square, being provided mainly by trees. Mean Sky View Factor obtained is 0.37 (partially shaded), which was calculated uploading fish-eye photos of nine selected locations into the software RayMan v. 1.2 (Matzarakis, 2007).

2.2 Data Collection

Micrometeorological measurements were taken at the same time that questionnaire surveys were conducted. Data were collected under clear-sky conditions in winter (July 18 and 22, 2015), spring (November 10 and 12, 2015) and summer (February 20, 2016), comprising a total of five days of measurements and 524 valid thermal comfort questionnaires. Considering the population size of Campo Grande, a minimum of 400 questionnaires (5% sampling error) can be considered as an acceptable sample size, according to the equation proposed in Barbetta (2006). Only permanent visitors were included in the research, passers-by were excluded. This is justified by the fact that thermal discomfort does not result in serious consequences when exposure time is short. On the other hand, prolonged exposure can be harmful to human health (Nikolopoulou et al., 2001; Thorsson et al., 2004).

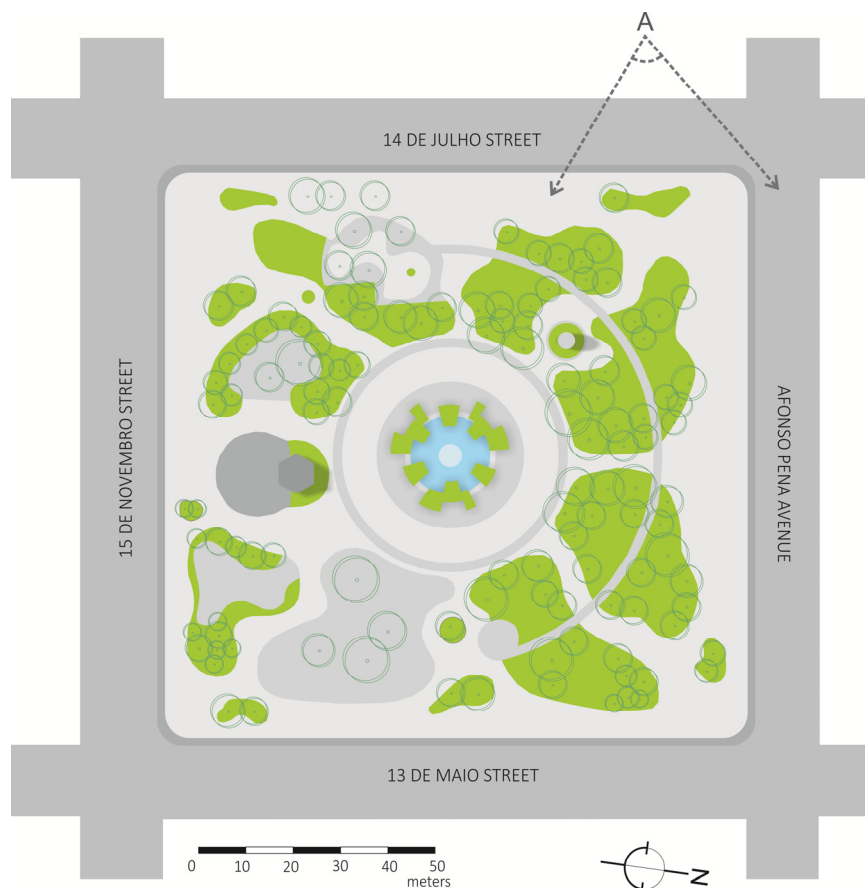


Figure 2. Investigated site, Ary Coelho Square.



Figure 3. Bird's-Eye View A.

2.2.1 Micrometeorological Monitoring

A calibrated microclimatic station BABUC-A was used in the monitoring, which was mounted on an adjustable tripod at 110 cm and placed on the southwest portion of the square (for practical and safety reasons). Climate variables monitored included: air temperature ($^{\circ}\text{C}$), air humidity (%), wind speed (m/s) and globe temperature ($^{\circ}\text{C}$). The collected data were stored into a data logger, processed through InfoGAP software and then averaged over 1 minute. Measurements were taken from 0900 until 1200 in winter and spring, and from 1400 until 1700 in summer, so that a wide range of climate conditions would be covered. Mean radiant temperature was estimated using RayMan v. 1.2 (Matzarakis 2007) model. Monitoring was performed following ISO 7726 (1998). Even though the Standard provides guidance for measuring physical variables in indoor environments, it has successfully been applied in outdoor thermal comfort studies as well (Silva & Alvarez, 2015; Ruiz & Correa, 2015).

2.2.2 Questionnaire Surveys

The thermal comfort questionnaire was applied randomly within the perimeter of the square. It was essentially divided in three parts: Personal Variables (1), Thermal Adaptation (2), and Thermal Sensation Vote (TSV) (3). Personal Variables (1) referred to the respondents' personal information, such as age, height, weight, gender, clothing insulation and metabolic rate. Metabolic rate is related to the degree of activity of the body. It was estimated in accordance with ISO 7730 (2005) and represented in the unit 'met'. Clothing insulation was estimated according to the same Standard and its value represented in the unit 'clo'. Such information was necessary to calculate the thermal index of each individual. In the Thermal Adaptation (2) section, people were asked about their behavioral adjustments when feeling hot (for example: seek shade of tree, drink cold beverage) and motivation to visit the square (necessary to evaluate if the individual remained in the square by choice or against their will). To acquire the Thermal Sensation Vote (TSV) (3), respondents were asked how they were feeling at that moment. The answer options were organized in a seven-point scale, ranging from "very cold" (-3), "cold" (-2), "slightly cold" (-1), to "neutral" (0), "slightly hot" (+1), "hot" (+2) and "very hot" (+3). The scale was elaborated following the recommendations of Standard ISO 10551 (1995), which provides guidelines to assess the thermal environment through judgment scales.

2.3 Thermal Index

Thermal indices are used to quantify and assess predicted comfort sensation votes. The thermal index used in this study was the Physiological Equivalent Temperature (PET) (Mayer & Höppe, 1987), which is one of the most used outdoor thermal comfort indices around the world. PET's wide application enables the comparison of results of this study with others in different geographic and climatic contexts. The index was calculated based on the following climatic variables: air temperature ($^{\circ}\text{C}$), air velocity (m/s) and relative humidity (%); all measured at 110 cm above surface. Such variables, collected during field campaigns, were then used as input data in RayMan v. 1.2 (Matzarakis 2007), which is a widely used public domain microclimatic model. The software's popularity can be partly explained by its ease of use and by the fact that it can estimate mean radiant temperature, a difficult variable to calculate (Gómez et al., 2013). Indeed, mean radiant temperature was estimated using the model.

PET result is expressed quantitatively in degrees Celsius (°C) and the correspondent thermal sensation can be estimated based on a nine-degree interpretative range. Ideally, this scale must be regionally adjusted based on subjective votes obtained in field campaigns. The calibration of PET's assessment ranges for the physiological reality of Campo Grande's inhabitants was proposed in Lucchese et al. (2016) and it was adopted in this study with a few adjustments (Table 1).

Table 1. Calibrated PET assessment scale for Campo Grande/Brazil

TSV equivalent	Sensation	PET-Central Europe (°C) (conventionally used scale)	PET-Campo Grande (°C) (regionally-calibrated scale)
-3	Very cold	$PET \leq 4$	$PET \leq 11$
-2	Cold	$4 < PET \leq 8$	$11 < PET \leq 15$
	Cool	$8 < PET \leq 13$	-
-1	Slightly cool	$13 < PET \leq 18$	$15 < PET \leq 21$
0	Neutral	$18 < PET \leq 23$	$21 < PET \leq 27$
+1	Slightly warm	$23 < PET \leq 29$	$27 < PET \leq 33$
	Warm	$29 < PET \leq 35$	-
+2	Hot	$35 < PET \leq 41$	$33 < PET \leq 39$
+3	Very hot	$PET > 41$	$PET > 39$
References		Matzarakis and Mayer (1996)	Lucchese et al. (2016)

3. Results and Discussion

3.1 Relationship between Microclimatic Variables and Thermal Sensation Votes

3.1.1 Mean Radiant Temperature and Air Temperature

During the five days of field campaigns, the minimum air temperature monitored in the square occurred in winter (15.3 °C) and maximum in spring (32.3 °C). As for mean radiant temperature, minimum occurred in winter (17.3 °C) and maximum in summer (34.4 °C). Many studies have emphasized the importance of mean radiant temperature in the assessment of outdoor thermal comfort conditions (Thorsson et al., 2004; Matzarakis et al., 2007; Krüger et al., 2011). In situations of sun exposure, mean radiant temperature can be regarded as a parameter that more accurately assess outdoor thermal comfort conditions than air temperature, which is the main variable conventionally adopted (Minella et al., 2011). Pearson correlation coefficients resulting from the association between the climate variables and thermal sensation votes were compared. Indeed, the results indicate a slightly greater association between TSV and mean radiant temperature ($r^2 = 0.55$) than TSV and air temperature ($r^2 = 0.54$). Since sensation votes are a subjective parameter, correlations were interpreted based on Cohen (1988). The author defined a value of 0.1 as of small, 0.3 as of medium and 0.5 or greater as of large association between variables (in the context of behavioral science).

3.1.2 Relative Humidity

During the experiment, the minimum relative humidity monitored in the square occurred in winter (42.6%) and maximum also in winter (68.2%). To assess if the variable was perceived by people positively or negatively, thermal sensation votes were distributed in PET intervals, in groups of different relative humidity ranges (Figure 4). The results indicate that relatively high values of relative humidity (60-70%) did not cause desirable effect on the visitors' thermal conditions when PET values were below 20 °C and above 30 °C PET. Comparing the amplitude of each relative humidity range, 60-70% had votes most distant from the central line of comfort (TSV=0). That is, the longer the arrow, more uncomfortable people were within that range. 40-50% range was stated as the most comfortable condition for the square visitors.

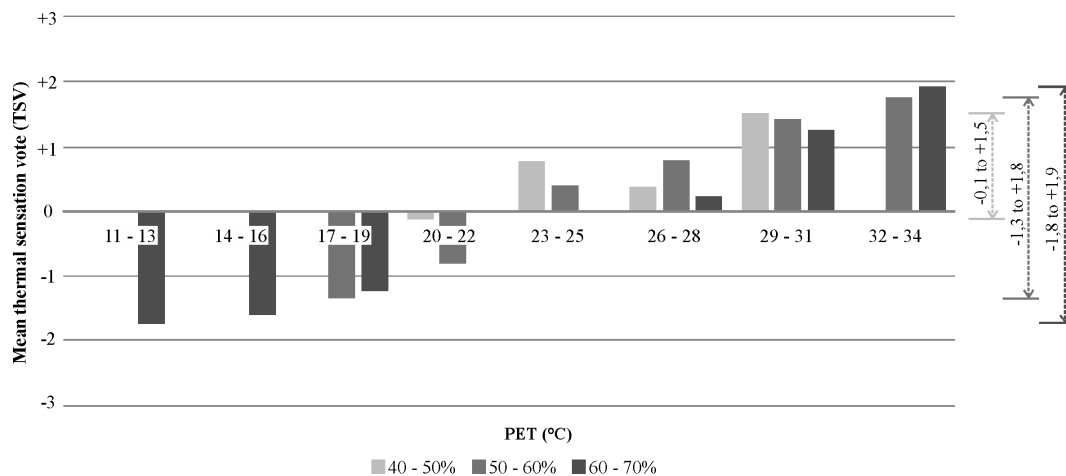


Figure 4. Amplitude of sensation votes as a function of PET ranges regarding relative humidity.

3.1.3 Wind Speed

During the field campaigns, the minimum wind speed monitored in the square occurred in spring (0.1 m/s) and maximum also in spring (5.5 m/s), all measured at 110 cm. Ventilation accelerates the heat exchange between the human body and the environment, which makes it a particularly important cooling strategy in tropical humid climate zones (Silva & Alvarez, 2015). During hot seasons, high air velocities have a desirable effect but during cold seasons, high wind speeds can result in thermal discomfort. The amplitude of the sensation votes was analyzed (Figure 5). The results indicate that, within the range 11-16 °C PET, wind caused undesirable cooling to most people. Air velocity of 1 m/s was desirable in the range 17-22 °C PET but it was insufficient to provide thermal comfort conditions at such speed after this interval. Within the range 23-25 °C PET, winds of 3 to 4 m/s provided thermal comfort to most respondents. From 28 °C PET on, wind ceased to provide comfortable cooling (even at high speeds) and started to cause undesirable heating by convection.

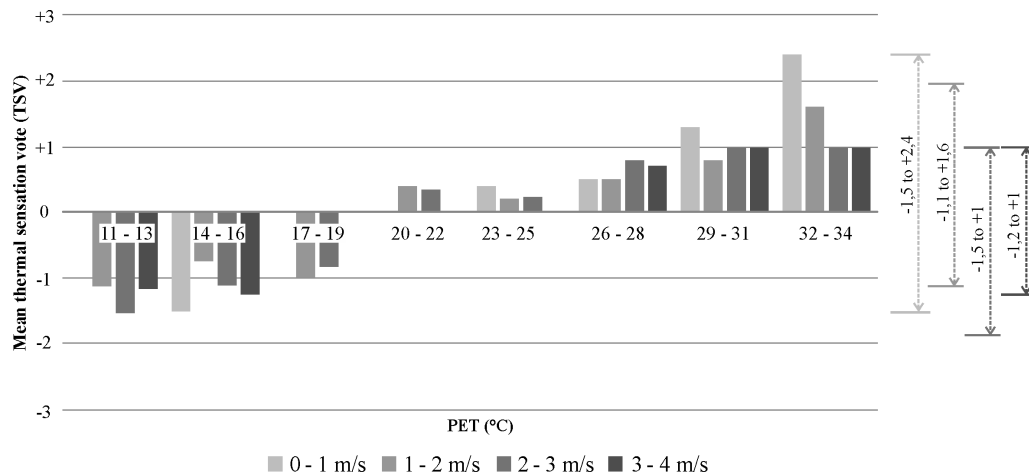


Figure 5. Amplitude of sensation votes as a function of PET ranges regarding air velocity.

3.2 Relationship between Thermal Adaptation and Thermal Sensation Votes

3.2.1 Behavioral Adaptation

Changes in the environment, that result in thermal discomfort, induce people to take behavioral actions seeking to restore their comfort conditions (Nicol, 2004). With this in mind, interviewees were asked what their favorite adaptation strategies were when experiencing heat discomfort. Only heat discomfort was investigated because the local climate is characterized by an extended hot season. Most people stated that they move to an area shaded by trees (47%). Only 3% stated that they would rather move to an area shaded by an artificial structure. This could be explained by the psychological parameter "naturalness". According to Nikolopoulou and Steemers (2003), naturalness is based on the assumption that people are more tolerant to situations of discomfort when

natural elements, rather than artificial ones, predominate in the landscape. Another relevant strategy was drinking cold beverages (41%), which can be explained by cultural habits. The consumption of *tereré* is very popular locally, which is a traditional beverage made of *yerba mate* (crushed dried leaves) infusion with cold water. As verified by Lin et al. (2013), there are limitations to certain strategies, such as adjusting clothes, in hot-humid regions. According to the authors, people are unable to reduce clothing during hot seasons as they normally already dress minimally. This could explain why only 5% of the interviewees chose this option.

3.2.2 Perceived Control

One of the reasons why thermal adaptation outdoors is particularly interesting is due to the fact that people have little control over the source of discomfort in open spaces (Ruiz & Correa, 2015). Perceived control can be investigated by considering whether people remain in a given place by choice or against their will. Lin (2009) and Lin et al. (2013) demonstrated that the level of autonomy of people in Taiwanese public squares significantly influences their perception of the thermal environment. According to the authors, people with higher levels of autonomy are more satisfied with their thermal conditions and thus better tolerate discomfort. In this study, the results reveal that, within the same PET intervals, people with low and high autonomy stated different mean thermal sensation votes (Figure 6). This difference suggests that autonomous people have a larger thermal tolerance than non-autonomous people.

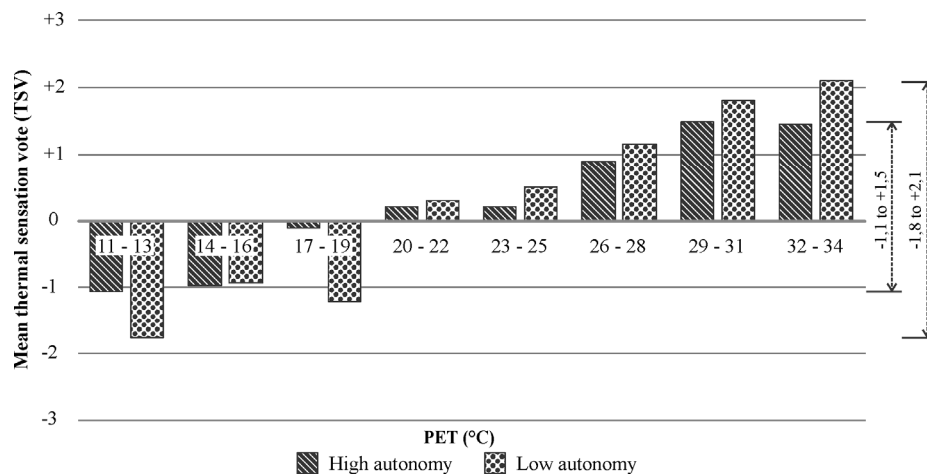


Figure 6. Amplitude of sensation votes as a function of PET ranges regarding autonomy levels.

3.2.3 Past Experience and Expectations

Past experience (physical, physiological and psychological) influences human thermal comfort, since expectation leads people to compare current with previous climate conditions. Thus, past experience in a particular place and time changes the way the thermal environment is perceived by people (Lin, 2009). This is particularly evident in the seasonal variation of neutral temperatures (that is, temperature where people feel neither warm nor cold) (Nikolopoulou, 2011). Seasonal variation of neutral temperature is an example of thermal adaptation linked to psychological factors because, under the physiological perspective, there should be no difference as seasons change.

Thermal sensation votes were analyzed based on the hypothesis that the temperature people feel comfortable with is that they have experienced before. Mean TSVs were grouped into 2 °C PET intervals and determined on a seasonal basis. A regression line was plotted and the equations for winter (1), spring (2) and summer (3) were estimated, which determine neutral PET temperatures (when mean TSV=0). The value obtained for winter was 23.1 °C PET, spring 23.3 °C PET and summer 24.4 °C PET.

$$\text{Winter: } TSV_{mean} = 0.1629 \cdot PET - 3.7686 \quad (1)$$

$$\text{Spring: } TSV_{mean} = 0.1971 \cdot PET - 4.5895 \quad (2)$$

$$\text{Summer: } TSV_{mean} = 0.1905 \cdot PET - 4.6561 \quad (3)$$

Similar studies have found different neutral temperature values in different seasons (Table 4). Lin (2009) demonstrated that experience reminds people that the air temperature in summer is higher than in winter, hence people's tolerance for high temperatures in summer is high, and its neutral temperature is higher than in winter.

The same study suggests that, as the annual variation of temperature increases, the difference between the neutral temperatures also increases. This indicates that the annual temperature variance of a given region influences the adaptation of local residents. These are in accordance with results found in this study.

Table 4. Neutral temperatures in different geographic and climatic contexts

Climate and location	Hot season (summer)	Cold season (winter)	Difference	Annual variation of air temperature	Reference
Temperate (Cambridge/ UK)	28 °C	8 °C	20 °C	28 °C (1 to 29 °C)	Nikolopoulou et al. (2001)
Humid subtropical (Sydney/ Australia)	33 °C	23 °C	10 °C	31 °C	Spagnolo and De Dear (2003)
Hot-humid (Taichung/ Taiwan)	25.6 °C PET	23.7 °C PET	1.9 °C PET	17 °C (18 to 35 °C)	Lin (2009)
Hot-humid (Campo Grande/ Brazil)	24.4 °C PET	23.1 °C PET	1.3 °C PET	14 °C (16 to 30 °C)	This study

3.3 Estimating Local Discomfort Hours

To estimate the hours of critical discomfort locally, mean PET values were calculated hourly for winter, spring and summer months. Climatic data used were obtained from Campo Grande's EnergyPlus weather file (EPW) format, downloaded from the U.S. Department of Energy website (historical series 1973-1991). Clothing insulation was set as constant based on the mean values obtained in the field campaigns: for winter 0.6 clo, spring 0.5 clo and summer 0.5 clo. Default value for metabolic rate was used (80W).

A thermal condition can be considered "acceptable" when TSVs are "slightly hot" (+1), "comfortable" (0) or "slightly cold" (-1) (ISO 7730, 2005). Thus, these votes were grouped in a central "no thermal stress" zone. Applying the regionally-adjusted PET interpretative scale (Table 2), discomfort hours were estimated for winter (Figure 7), spring (Figure 8) and summer (Figure 9) months.

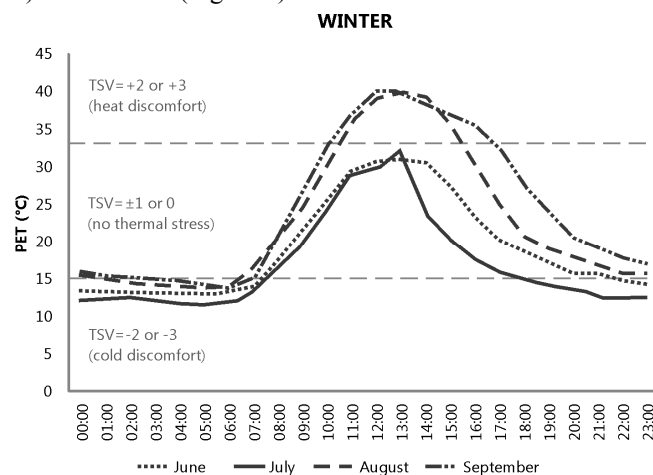


Figure 7. Estimated discomfort hours in winter months.

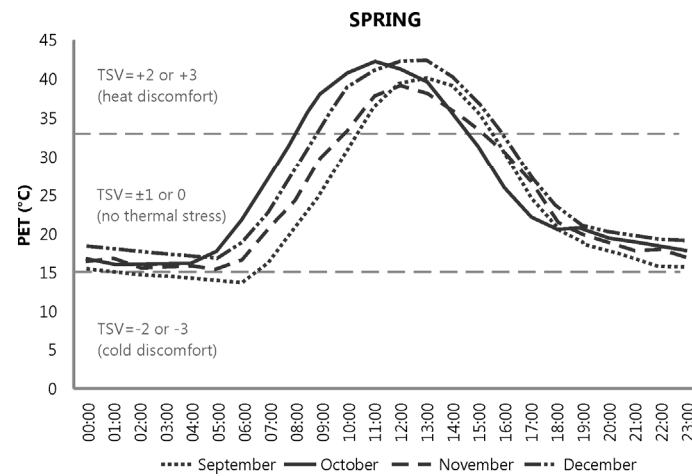


Figure 8. Estimated discomfort hours in spring months.

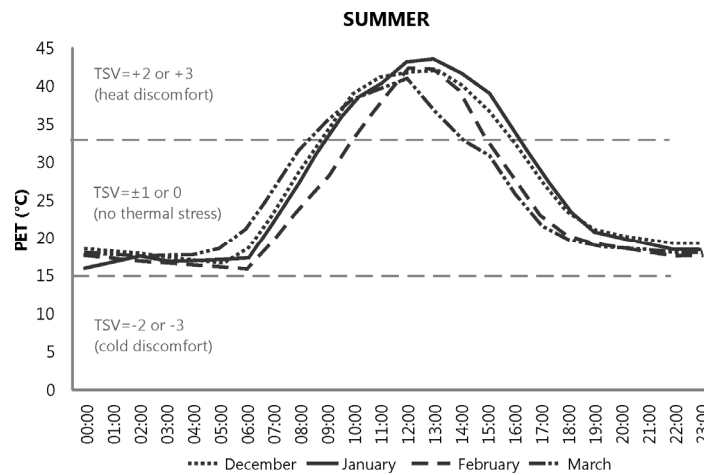


Figure 9. Estimated discomfort hours in summer months.

Winter provides more discomfort hours (48% average) than spring (32% average) and summer (28% average). However, (cold) discomfort hours in winter prevail between 0000 and 0700, when public squares do not have a significant number of visitors. During spring and summer, (heat) discomfort hours prevail when public squares have high flow of visitors (0730 to 1700). The results reinforce the importance of providing improved microclimate conditions in urban open areas, aiming to encourage greater use of open spaces and increased length of stay of visitors.

4. Conclusions

The results reaffirm that psychological and behavioral factors influence the individuals' assessment of the outdoor thermal environment and therefore should be considered as design criteria. To improve the microclimate of urban open areas in Campo Grande, shading must be provided primarily by trees, given the preference of respondents for naturally-shaded spaces. Furthermore, trees decrease both air temperature and mean radiant temperature and such variables are strongly related to outdoor thermal sensations. Resting places should be protected from direct wind exposure using removable barriers (used according to necessity). The use of water features for evaporative cooling purposes is not recommended, since lower relative humidity values provide better comfort conditions. However, drinking fountains should be available in public squares of Campo Grande. It is of great importance that different microclimates are provided in urban open areas, so that visitors can have the opportunity of choice (perceived control) throughout the day and seasons according to their personal needs. Nevertheless, such microclimates should be mostly designed to provide cooler conditions, since visitors are more exposed to heat discomfort.

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