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Daytime thermal comfort in urban spaces: A field study in Brazil

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A B S T R A C T

This article presents the results from thermal comfort surveys in two squares located in the city of Belo Horizonte, Brazil over two different seasons. Objective environmental parameters were compared with subjective responses collected during field surveys in order to evaluate thermal comfort conditions people experience and identify potential thermal adaptation processes. Individuals and behavioral' characteristics were also taken into account. The summer survey was carried out in March 2013 and the winter survey in July 2013, both comprising a total of 1693 interviewees. The PET index was calibrated to determine the thermally acceptable range. Neutral and preferred temperatures, for both summer and winter, were obtained in order to assess thermal preference. The results show that people were more tolerant in one of the squares (*Liberdade* square) in winter, considering the same thermal conditions. These findings were associated to psychological processes related to thermal adaptation, such as naturalness, perceived control, experience (thermal history on longer timescales – seasonal) and environmental diversity - along with the presence of greater adaptive opportunities. The calibration of the PET index, resulted in the definition of the thermal acceptability range of: “Cold” for PET values bellow 19 °C; “Neutral” for PET values between 19 °C and 27 °C; “Hot” for PET values greater than 27 °C. Neutral temperatures were 27.7 °C, in summer, and 15.9 °C, in winter; while preferred temperatures were 14.9 °C, in summer, and 20.9 °C, in winter. Design strategies, such as shading, exposure to the wind and providing increased environmental diversity may improve urban environments and pedestrians' experience in cities.

1. Introduction

In urban open public spaces, particularly in big cities of tropical climate, pedestrians are often exposed to high thermal loads, which can cause thermal discomfort. Suitable conditions for thermal comfort in urban environments can be obtained through the proper treatment of these spaces, which can in turn encourage walking, improve urban microclimate, reduce energy consumption, etc., with implications for the wider city [1,2].

A recent review of outdoor thermal comfort studies revealed that focusing on human perception beyond thermophysiology enabled a more holistic understanding of outdoor thermal comfort [3]. Nikolopoulou and Steemers [4] showed that only 50% of the variance in the evaluation of subjective comfort was explained by physical parameters, indicating that psychological processes may be involved in the thermal assessment of outdoor environments. Therefore, outdoor thermal comfort indices may not be applicable in different cultural/climate zones without modifications and without being calibrated, and they may not be appropriate if the psychological processes involved in environmental assessment are not taken into account, as cultural characteristics markedly impact the assessment of thermal comfort, even in similar thermal conditions [5,6]. In addition, field surveys revealed that a purely physiological approach is inadequate to characterize the conditions of thermal comfort outdoors, and the concept of adaptation has become critical [7].

Thermal adaptation, which involves physiological, psychological

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and behavioral factors, plays an important role in the assessment of thermal comfort in outdoor environments by users [4]. By separating thermal sensation from thermal satisfaction, it was further demonstrated that 'adaptive opportunity', that is, the degree to which people can adapt to their environment, is important for their satisfaction with the space [2]. As physiological adaptation to a climate is generally slow it is not critical for thermal comfort studies in urban spaces. Conversely, the impacts of physical (behavioral adjustments) and psychological adaptation (expectation, past experience, time of exposure, environmental stimulation, perceived control, naturalness) on thermal comfort are significant [4,8,9].

Studies investigating thermal adaptation in hot and humid regions have examined how psychological factors influence thermal comfort, indicating that individuals residing in these regions have greater tolerance for high temperatures than those residing in temperate regions [9]. The comparison of thermal sensation of people in Mediterranean and subtropical climates indicates that people have different thermal comfort ranges [10], which are significantly higher [9] or wider [11,12] for tropical climates than those obtained for Central and Western Europe.

With respect to the seasons, in winter people tend to prefer higher temperatures, while in summer the opposite is observed [13], that is, they tend to prefer lower temperatures [14,15], which can be explained by the concept of alliestesia, i.e., shifts in the pleasantness or unpleasantness of a stimulus depending on one's internal state [16]. The concept of alliesthesia, originally proposed by Cabanac in the 1970s [17] is presented as a psychological mechanism that explains these differences in sensation between seasons (long-term), which is defined as perceptual alliesthesia [14]. The individuals perception of the previous season is desensitised by their perception of their recent (hours to days) thermal history, and then, in winter people long for the warmer conditions of the summer months, while in the heat of summer, they long for the cooler winter conditions [14]. In their studies, Spagnolo and De Dear suggested evidence of a seasonal difference in thermal neutrality and preference in outdoor areas [14]. A more recent study conducted in northern China [18] shows that thermal sensation and overall comfort can vary with the season.

Focusing on the Brazilian city of Belo Horizonte, the current study aims to assess outdoor thermal comfort and investigate the potential for thermal adaptation. The Physiological Equivalent Temperature (PET), introduced by Mayer and Höppe in 1987 [19], was used to quantify thermal sensations. This thermal index is based on a thermo-physiological heat-balance model and has been widely adopted in thermal comfort assessments in outdoor environments [20]. Originally PET had no reference ranges for its interpretation, but has been calibrated for some cities across the world [9–12,18,21–26]. Recently, it has also been calibrated for the city of Belo Horizonte, initially by Hirashima [27], and then by Hirashima, Assis and Ferreira [28], which enabled them to define ranges of PET for different degrees of thermal perception, i.e.: 'cold', up to 12 °C; 'slightly cold', from 12 °C to 15.5 °C; 'comfortable', from 15.5 °C to 30.5 °C; 'slightly hot', from 30.5 °C to 31 °C; 'hot', from 31 °C to 35.5 °C; and 'very hot', above 35.5 °C [28]. In the present article, the results of the studies carried out by Hirashima [11] will be presented. The PET index was recalibrated (a larger sample was used to define the intervals) and neutral and preferred temperatures, for both summer and winter, were also calculated in order to assess thermal preference. By comparing these results with those obtained from different regions in previous studies, this study sheds light on outdoor thermal comfort in a tropical climate region, identifies thermal adaptation processes and proposes design strategies to mitigate microclimatic conditions.

2. Methodology

2.1. Study area

Belo Horizonte (19°55′S, 43°56′W) is in a tropical climate zone, classified as an Aw climatic type according to Koeppen-Geiger's climate classification, which corresponds to the wet tropical climate with average temperature of the coldest month above 18 °C and distinct dry season in winter [29]. According to Normais Climatológicas do Brasil (1961–1990) to Belo Horizonte, the average annual air temperature is 21.1 °C, while the average annual relative humidity is 72.2%. Low velocity winds occur throughout the year (about 1.5 m/s) and the prevailing direction is East [30]. The average monthly precipitation observed during the period between 2000 and 2012 was 276 mm (November to March) and 42 mm (April to October) [31].

To evaluate the different microclimatic conditions and to obtain the widest range of the PET index, two case study areas were selected *Liberdade* square (Fig. 1) and *Sete de Setembro* square (Fig. 2), considered for their contrasting characteristics of urban morphology, regarding the sky view factor, height of buildings, type of surface (paved or not) and the presence of water features and vegetation. Another aspect considered in the selection of the areas was the intense flow of people, to enable the administration of a large number of questionnaires. In order to obtain the largest amplitude of thermal conditions spatially, two points were selected for the measurements and for the administration of the

Fig. 1. *Liberdade* square: low-rise buldings, green areas, wide sky view factor, permeable surfaces and water features.

Fig. 2. *Sete de Setembro* square: high-rise buldings, few trees, narrow sky view factor, paved surfaces, no water features.

questionnaires in each square: one in the sun, and another in the shade.

2.2. Physical measurements

The summer data collection occurred on 11th March 2013 at *Liberdade* square (Fig. 1), and on 13th March 2013 at *Sete de Setembro* square (Fig. 2). The winter data collection was carried out on 08th July 2013 at at *Liberdade* square, and on 09th July 2013 at *Sete de Setembro* square. Both data collections occurred from 7.00am to 5.00pm, so that the largest thermal diurnal amplitude could be recorded. The selection of the equipment and procedures used to measure microclimate variables (air temperature, relative humidity, wind speed and globe temperature) took into account the recommendations of ISO 7726 [32]. The instruments (thermometer, hygrometer, anemometer and globe thermometers) were assembled on tripods, 1.1 m high, 30 min before the start of the survey - time required for the globe thermometer to reach equilibrium. Since the measurements were carried out outdoors and a faster response time was required, a 40 mm-diameter grey globe thermometer was used [32–34]. All instruments were previously calibrated and gauged. All data were recorded every 5 min.

2.3. Questionnaire survey

In addition to the microclimatic variables measured, variables that directly or indirectly influence the thermal perception were collected during field surveys, by means of structured interviews and observations: individual variables (age, sex, height, weight, metabolic rate, thermal insulation of clothing, location of respondent - if in the sun or in the shade and sensitivity to climatic conditions) and subjective variables (perception of thermal sensation, preference of thermal sensation and evaluation of thermal comfort). The elaboration of the questionnaire considered the related international standards ISO 10551 [35], ISO 7730 [36], ISO 8996 [37] and ISO 9920 [38]. The section of the questionnaire related to thermal perception, thermal comfort and thermal preference observed the international standard ISO 10551 [32], which establishes the subjective judgment scales for thermal stress – perceptual, evaluation and preferential judgment scales. For thermal perception assessment (question: "How are you feeling at this precise moment?"), a symmetrical 7-degree two-pole scale was used: *very hot, hot, warm, neutral (neither hot nor cold), cool, cold and very cold.* For thermal comfort evaluation (question: "Do you find this …"), a 4-degree one-pole scale was used: *comfortable, slightly uncomfortable, uncomfortable, very uncomfortable*. For thermal preference assessment (question: "Please state how you would prefer to be now"), a symmetrical 7-degree bipolar scale was used: *much warmer, warmer, slightly warmer, no change – neither warmer nor cooler, slightly cooler, cooler, much cooler*. The sample frame considered the adult population (20–59 years-old) residing in the city for more than one year and that was in outdoors environments

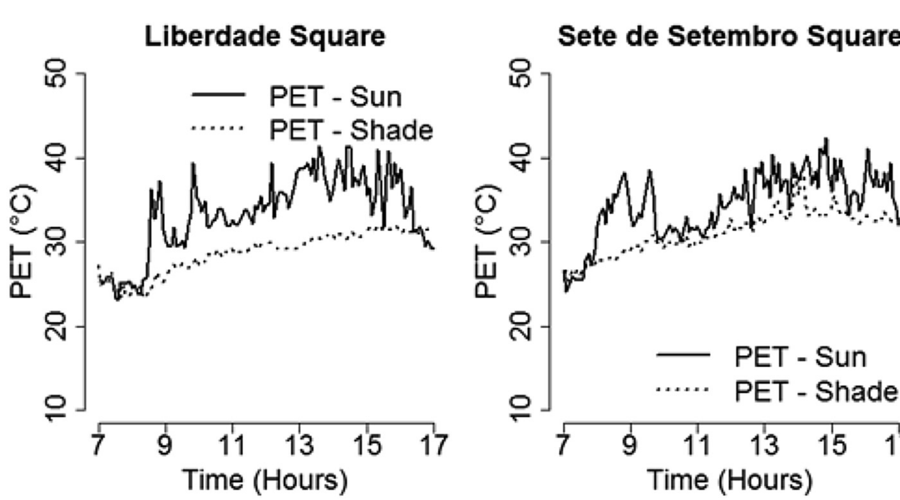

Fig. 3. Temporal series of PET (°C), for summer survey.

for more than 30 min.

2.4. Statistical treatment of collected data

The analysis of the collected data began with the calculation of the mean radiant temperature (Tmrt) and the PET index. Since the measurements were carried out outdoors, the equation established by ISO 7726 [32] for forced convection was used to calculate the Tmrt, based on a 40 mm-diameter grey globe temperature values. The PET was calculated by using a software developed at the University of Freiburg, version Holst [39]. In order to relate objective (measured variables) to subjective data (personal responses from interviewees), statistical treatment of data was performed using descriptive analysis, regression models (ordinal logistic regression, logistic regression) and probit analysis. In this article, the responses categories were regrouped into 3 categories: for thermal perception: "Hot" (*very hot, hot, warm),* "Neutral" *(neither hot nor cold) and* "Cold" *(cool, cold and very cold);* For thermal comfort: "Comfortable" (*comfortable) and* "Uncomfortable" *(slightly uncomfortable, uncomfortable, very uncomfortable);* For thermal preference: "Warmer" (*much warmer, warmer, slightly warmer*), "No change" – *neither warmer nor cooler* and "Cooler" *(slightly cooler, cooler, much cooler).*

3. Results

A total of 1693 questionnaires were administrated during the field surveys, 835 during the summer and 858 questionnaires during the winter survey, which means a sampling error of, approximately, 7%. Raw microclimatic data, as well as subjective, indivudual and behavioral data, can be accessed in Ref. [40].

Figs. 3 and 4 present the temporal series of PET for both squares, in the summer and winter surveys respectively. In addition, Table 1 shows the minimum (MIN), the mean (MEAN) and the maximum (MAX) values of the PET index, the standard deviation (SD) and coefficient of variation (CV), for both points (sun and shade), in both squares and for both field surveys.

Considering the PET data shown in Figs. 3 and 4 and in Table 1, the highest values of the PET index were recorded in the sun. This result is consistent with those obtained for other microclimatic variables (mainly for the globe temperature), since in situations in which the measurements were carried out in the sun, the values were higher than those measured in the shade, also resulting in higher values of PET. However, the measured values in the sun did not always result in higher values of PET, since it was also in the point placed at the sun that higher wind speed values were measured. For the points located in the shade, the calculated values of PET have lower variability and less dispersion than those in the sun.

Although it is not possible to compare the monitored values at *Liberdade* square with those in *Sete de Setembro* square directly, since measurements were performed on different days, in the summer surveys, the average values of PET in *Sete de Setembro* square were higher. In the winter survey, the reverse occurred with average values of PET in *Liberdade* square being higher. This result is consistent with the average air temperature recorded in both squares.

Table 1
Values of the thermal index PET (°C), for summer and winter survey.

	Summer survey				Winter survey			
	Liberdade square		*Sete de Setembro* square		*Liberdade* square		*Sete de Setembro* square	
	Sun	Shade	Sun	Shade	Sun	Shade	Sun	Shade
MIN	23,1	23,3	24	25,4	17,7	16,6	14,3	16,2
MED	33,4	28,7	34,5	31,2	26,1	22,6	23,1	21,1
MAX	41,4	32	42,4	38,6	32,1	29,5	31,4	25,6
SD	4,7	2,5	4	2,6	4,6	3	3,8	2,5
CV (%)	14	8,6	11,5	8,2	17,6	13,3	16,5	11,8

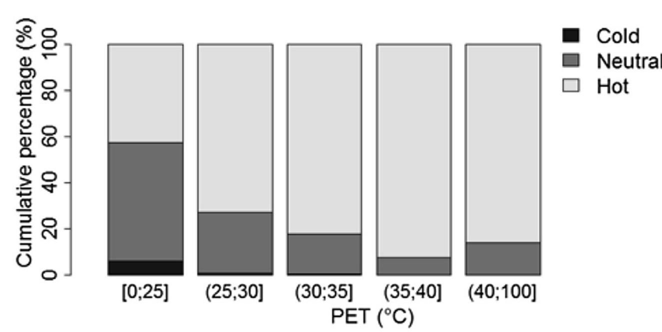

Fig. 5. Percentile distributions of thermal sensation categories as a function of the PET (°C), in *Liberdade* square, summer survey.

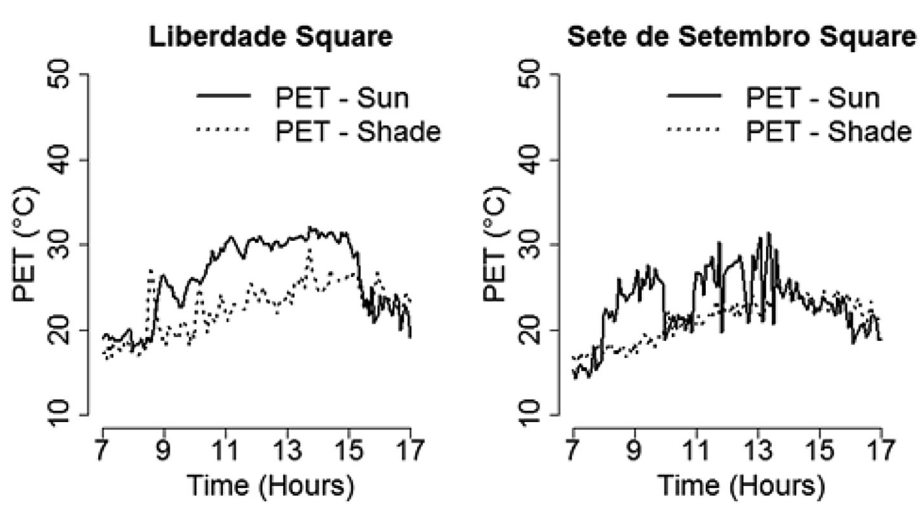

Fig. 4. Temporal series of PET (°C), for winter survey.

3.1. Thermal sensation and evaluation of thermal comfort

Pedestrians' thermal sensation in relation to PET is presented for *Liberdade* square and for *Sete de Setembro* square, in summer (Figs. 5 and 6, respectively) and in winter (Figs. 7 and 8, respectively). Similarly, evaluation of thermal comfort in relation to the PET is presented for *Liberdade* square and for *Sete de Setembro* square, in summer (Figs. 9 and 10, respectively) and in winter (Figs. 11 and 12, respectively).

Regarding the perception of thermal sensation (Figs. 5 and 6) and the evaluation of thermal comfort (Figs. 9 and 10), during the summer survey, in both squares, the majority of respondents reported that they were "Hot" and "Uncomfortable", with a small percentage being "Neutral" and "Comfortable". This result may be expected; by analyzing the temporal series of PET shown in Fig. 3, it can be seen that, for most of the period studied, the values of PET were above 30.5 °C, which is the upper limit of the comfort range defined by Hirashima et al. (2011) [28]. Likewise, for a long period of the time studied, the values of PET were above 35.5 °C, threshold above which people are too hot, according to the calibration

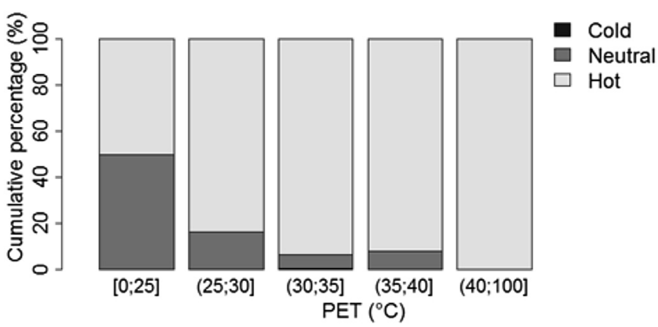

Fig. 6. Percentile distributions of thermal sensation categories as a function of PET (°C), in *Sete de Setembro* square, summer survey.

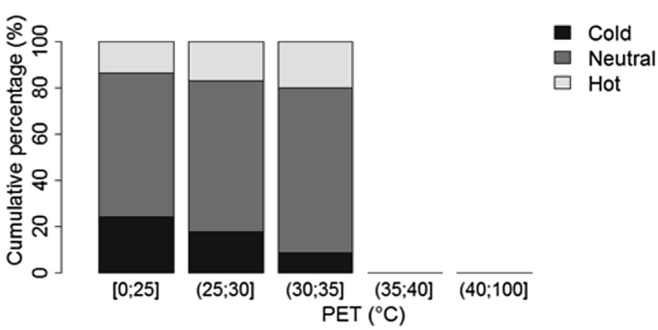

Fig. 7. Percentile distributions of thermal sensation categories as a function of the PET (°C), in *Liberdade* square, winter survey.

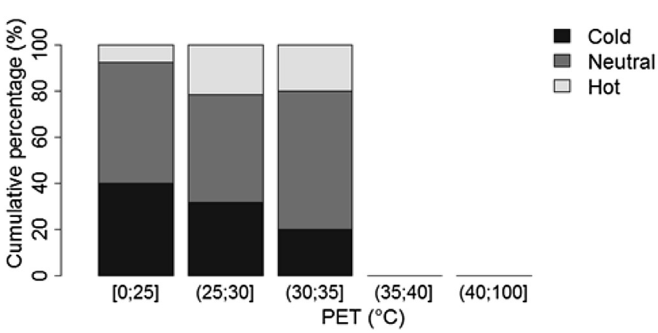

Fig. 8. Percentile distributions of thermal sensation categories as a function of PET (°C), in *Sete de Setembro* square, winter survey.

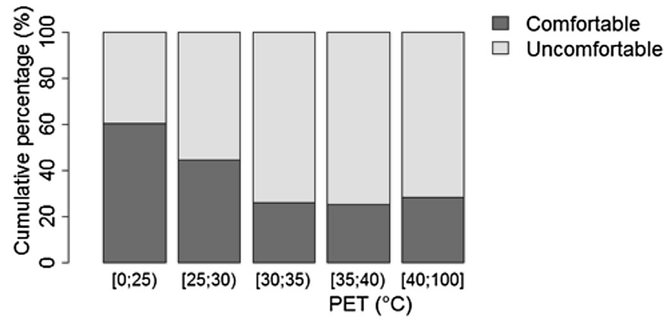

Fig. 9. Percentile distributions of thermal comfort evaluation categories as a function of PET (°C), in *Liberdade* square, summer survey.

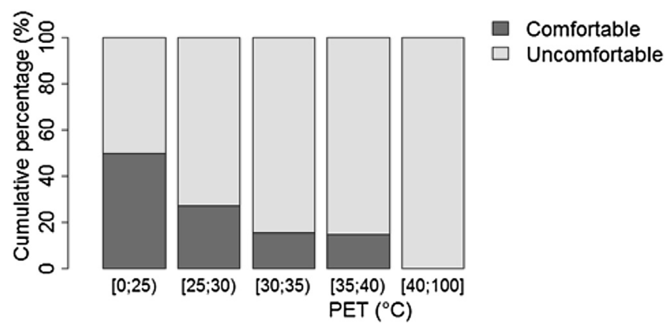

Fig. 10. Percentile distributions of thermal comfort evaluation categories as a function of PET (°C), in *Sete de Setembro* square, summer survey.

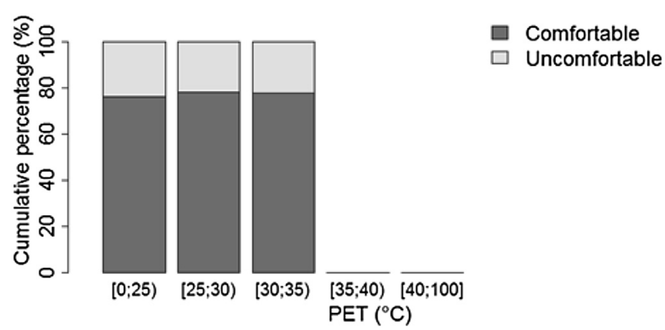

Fig. 11. Percentile distributions of thermal comfort evaluation categories as a function of PET (°C), in *Liberdade* square, winter survey.

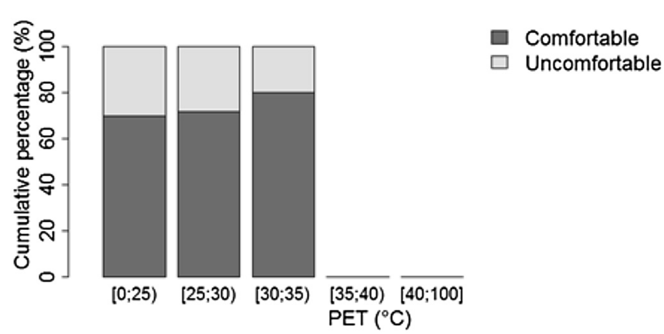

Fig. 12. Percentile distributions of thermal comfort evaluation categories as a function of PET (°C), in *Sete de Setembro* square, winter survey.

performed by the same study [28]. This may explain the high percentage of people reporting being “Hot”.

Regarding the perception of thermal sensation (Figs. 7 and 8) and the evaluation of thermal comfort (Figs. 11 and 12), during the winter survey, in both squares, the majority of respondents reported that they were “Neutral” and “Comfortable”. This may also be expected as by analyzing the temporal series of PET shown in Fig. 4, it can be seen that, for most of the period studied, the values of PET were inside the comfort range defined by Hirashima et al. (2011) [28], which is 15.5–30.5 °C.

In both seasons, when considering the same thermal conditions - for all PET intervals addressed, the percentage of people who felt “Neutral” is greater in *Liberdade* square than in *Sete de Setembro* square (Figs. 5–8). Similarly, the percentage of people who felt “Comfortable” is also greater in *Liberdade* square (Figs. 9–12).

In both squares, when considering the same thermal conditions - for all PET ranges analysed, the percentage of people who felt “Neutral” is greater in winter (Figs. 5–8), as is also the percentage of people who felt “Comfortable” (Figs. 9–12).

Overall, the analysis of the graphs presented (Figs. 5–12), shows that, under the same thermal conditions, both regarding thermal sensation and thermal comfort, individuals appear to be more tolerant of the conditions in *Liberdade* square than in *Sete de Setembro* square and appear to be more tolerant in winter than in summer.

This greater degree of tolerance in *Liberdade* square and winter with respect to the same microclimate conditions may be explained by psychological factors related to the context in which the stimuli occur. The scenery in *Liberdade* square includes green areas, well looked after flowerbeds, water features, historic buildings that are part of the cultural heritage of the city, natural sounds like the birds as part of its soundscape, people strolling with children and pets. This is in sharp contrast to the build-up area of the *Sete de Setembro* square with heavy traffic. Hence the former site demonstrates higher degree of naturalness making it more enjoyable, while there is a greater degree of environmental diversity, providing greater adaptive opportunities, i.e. there are more options available with regard to places to sit or stand, shade or sun, protected or exposed, presence of water features, proximity or distance from the street, etc.

The greater level of tolerance in winter than in summer, may be attributed to the milder thermal conditions during this season when compared to the typical summer thermal conditions (which are often of thermal stress due to heat). Factors linked to experience with the thermal conditions seasonally and expectations can result in a greater tolerance in this season.

In the summer surveys, with respect to the thermal sensations separated by PET intervals (Figs. 5 and 6), it is noticeable that, in both squares, in the intervals representing PET values smaller than 25 °C, there is a higher percentage of people who reported being “Neutral”. Similarly, regarding the evaluation of thermal comfort (Figs. 9 and 10), in the same range of PET values smaller than 25 °C, in both places, there is also a higher percentage of people who are “Comfortable” with regard to the thermal conditions.

Conversely, in the winter survey, with respect to the perception of thermal sensations separated by PET intervals (Figs. 7 and 8), it is noticeable that, in both squares, in the intervals representing PET values higher than 25 °C (mostly between 30 and 35 °C), there is a greater percentage of people who reported being “Neutral”. Similarly, regarding the evaluation of thermal comfort (Figs. 11 and 12), in the same range of PET values higher than 25 °C (especially between 30 and 35 °C) in both places, there is also a higher percentage of people who say they are “Comfortable” with regard to the thermal conditions.

This difference in thermal sensations and thermal comfort between seasons can be explained in the context of adaptive comfort theory discussed earlier, and psychological adaptation, particularly related to expectations, past experience and perceptual

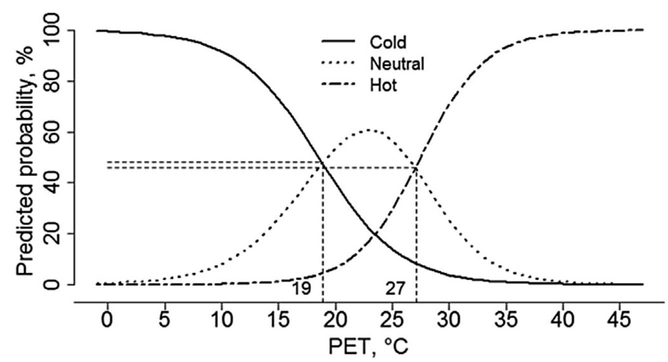

Fig. 13. Calibration of the PET thermal index for open spaces for Belo Horizonte, Brazil.

alliesthesia. This issue will be further discussed in Section 3.3. For this reason, a hypothesis can be put forward that the thermal sensation and the thermal comfort intervals, and consequently the comfort zone, may be slightly different for the same location between seasons.

Another issue worth highlighting is that the percentage of individuals in the category “Comfortable” of thermal comfort evaluation is higher than that in the category “Neutral” of thermal sensation (Figs. 9 and 5, 10 and 6, 11 and 7, 12 and 8), when the same thermal conditions are compared. This highlights the fact that a degree of thermal stimulation and contrast in the environment can be regarded as positive, i.e., thermal sensation of warm and cool, beyond the neutral category, can be assessed as comfortable conditions. This leads us to hypothesize that a calibration of the scale for evaluation of thermal comfort when compared to the calibration of the thermal sensation scale would result in a wider “Comfortable” range when compared to the “Neutral” interval.

3.2. Thermal acceptability range

Fig. 13 presents the definition of the intervals of the PET index (calibration) for thermal sensation for open public urban spaces of Belo Horizonte - Brazil, showing the predicted probabilities for thermal sensation in relation to the PET values.

In considering Fig. 13, it is possible to verify that when the PET value is bellow 19 °C, the thermal sensation is “Cold”; if the value of the PET is between 19 °C and 27 °C, people feel “Neutral” with regard to thermal conditions; and when the value of the PET is greater than 27 °C, the thermal sensation is “Hot”. Table 2 presents a comparison of the PET index interval “Neutral” established by previous studies, which represents a comfort situation with regard to thermal conditions.

By comparing the ranges obtained in this study with those presented in Table 2, it is possible to note that the range “Neutral” established in this study presents a greater amplitude than the range determined by Matzarakis et al. for Central Europe [21], and is slightly shifted to warmer thermal conditions. Comparing the “Neutral” range established in this study with the ranges established for cities of hot and humid weather (Taiwan and Salvador) it turns out that, although the intervals determined by Lin [9] and Souza [24], respectively, present similar amplitude when compared to the amplitude of the range determined by this study, these intervals are shifted to warmer temperature conditions. Regarding

Table 2
Comparison of the PET index interval "Neutral" established by previous studies.

References	PET index interval "neutral", in °C	City and/or region to which the intervals were established
MATZARAKIS, MAYER, IZIMON (1999) [21]	18–23	Central and Western Europe
MONTEIRO (2008) [22]	18–26	São Paulo/Brazil
LIN (2009) [9]	21.3–28.5	Taiwan
KATZSCHNER (2010) [23]	18–28	Kassel and Freiburg/Germany
SOUZA (2010) [24]	22–31	Salvador/Brazil
HIRASHIMA, ASSIS, FERREIRA (2011) [28]	15.5–30.5	Belo Horizonte/Brazil
HIRASHIMA (2014) [11]	19–27	Belo Horizonte/Brazil
LAI et al. (2014) [18]	11–24	Tianjin/China
SALATA et al. (2016) [26]	21.1–29.2	Rome/Italy

the previous calibration performed by Hirashima et al. [28] to Belo Horizonte, the range "Neutral" established in this study resulted from a larger sample (1182 and 1693 respondents respectively), which may have resulted in the band narrowing in the present study.

The interval "Neutral" established in the current study is very similar to the interval determined by Katzschner [23] and Monteiro [22]. However, it is worth noting that the range "Neutral" established in this study presents close similarities with the range set by Monteiro [22] for São Paulo, with the same amplitude and very similar limits. It should be noted that, according to NBR 15.220 - Thermal performance of buildings, Part 3: Brazilian bioclimatic zoning and construction guidelines for single-family social housing (ABNT, 2005) [41], São Paulo and Belo Horizonte are in the same bioclimatic zone, Zone 3, because they have climates with similar characteristics, which may explain the similarity between their thermal comfort ranges.

3.3. *Thermal preference*

In order to identify the thermal preference, neutral and preferred temperatures were calculated for both summer and winter. The neutral temperature represents the temperature at which people feel thermally neutral, i.e. neither cool nor warm, whereas the preferred temperature is the temperature people want [9].

To obtain the values of neutral temperatures, the mean thermal sensation votes (MTSVs) of respondents in each 1 °C PET interval group, in cool and hot seasons, were calculated and plotted. Fig. 14 presents the fitted regression lines and the equations of the functions that relate the average of the thermal sensation votes with PET values, for each of the seasons - winter and summer. Initially the absolute values of PET were considered, and then, the logarithm of the PET values, to improve the adjustment of the functions. It is worth noting that, in the current study, the logarithm of the PET values (Fig. 14) represented better the situations in question. By making the logarithm of PET (log (x)) equals zero, the result is the value of the neutral temperatures: 27.7 °C, in summer and 15.9 °C, in the winter.

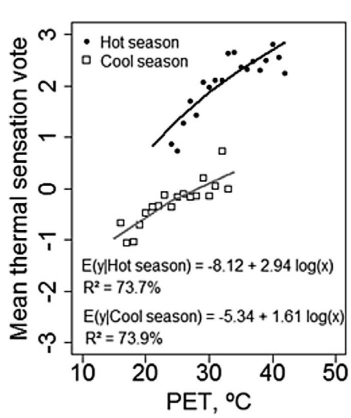

Fig. 14. Correlation between the mean thermal sensation votes (MTSVs) and PET in the cool and hot seasons, logarithm of the PET values.

To calculate the preferred temperature based on preference votes, i.e., votes for "want warmer" and "want cooler" temperatures, probit analysis was applied. These preferences were divided into groups for each 2 °C PET intervals, and the percentage of each preference was calculated within each groups and fitted with the probit model separately. Regressions were adjusted for want "cooler in cool season" and want "warmer in cool season", and want "cooler in hot season" and want "warmer in hot season". For each season, the point at which both models intersect is regarded as the preferred temperature, at which individuals do not prefer either a cooler or a warmer temperature, they prefer thermal conditions as they are in time, without changes. Taking into account the results from the probit analysis, the preferred temperature was 20.9 °C, in the winter, and 14.9 °C, in the summer (Fig. 15).

The preferred temperature of 14.9 °C for summer is due to the sharp drop in the number of people wanting warmer conditions in hot season with the increase of the PET. Subjective responses regarding the thermal preference assessment in summer show that 10.4% of the interviewees reported that they would prefer to be *much cooler* (in relation to the thermal conditions at the moment interviews were being conducted); 26.5% answered *cooler; 41.8% slightly cooler; 20% no change – neither warmer nor cooler.* Only 0.6% of the interviewees reported that they would prefer to be *slightly warmer; 0.4% warmer; and 0.2% much warmer.*

Table 3 shows the results of neutral and preferred temperatures, as well as thermal perception neutral interval, for the winter and the summer.

In winter, the preferred temperature is higher than the neutral temperature by 5 °C. Conversely, in the summer, the preferred temperature is lower than the neutral temperature by 12.8 °C.

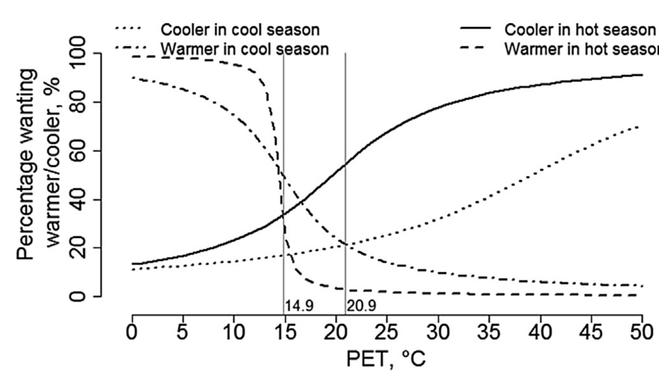

Fig. 15. Preferred temperatures in the cool and hot seasons.

Table 3
Thermal acceptable range, neutral and preferred temperature obtained in this study and comparison of values.

	Thermal perception - PET “neutral” interval, in °C	Neutral temperature – PET (°C)		Preferred temperature – PET (°C)	
		Winter	Summer	Winter	Summer
HIRASHIMA (2014) [11]	19–27	15.9	27.7	20.9	14.9
LIN (2009) [9]	21.3–28.5	23.7	25.6	23	24.5
SALATA et al. (2016) [26]	21.1–29.2	24.9	26.9	22.5	24.8

Therefore, during the winter, people feel neutral at 15.9 °C, but would like the temperature to rise to 20.9 °C. The difference between what people feel and what they prefer in terms of thermal comfort, is 5 °C. Conversely, during the summer, people feel neutral at 27.7 °C, but would like the temperature to decrease to 14.9 °C. The difference between what people feel and what they prefer, in terms of thermal comfort, is of 12.8 °C. These comparative results show that people long for cooler thermal conditions during the summer and for warmer thermal conditions during the winter, reinforcing the findings of Section 3.1. The results also highlight the impact of expectations and alliesthesia on thermal comfort. Although higher temperatures are expected in the summer leading to higher thermal neutrality, the preference is for lower temperatures, with preferred temperatures, for summer and winter, being lower when compared to the comfort range defined in Table 3.

The preference for cooler thermal conditions can also be related to the possibility of variation of the garment in order to adapt to the thermal conditions, which is not possible in warmer thermal conditions. The descriptive analysis show that, during the summer, in both squares, approximately 60% of the interviewees were using clothes with thermal resistance of 0.5clo. The thermal resistance of the garment of respondents varies more in winter than in summer (more balanced distribution of frequencies), with predominance of clothes with thermal resistance of 0,5 and 0,7clo. Another interesting fact was the predominance of the location of respondents in the shade in both squares and in both seasons. In *Liberdade* square, 60% of the interviewees in summer and 71% in winter survey, were in the shade during interview; while in *Sete de Setembro* square, 79% of the interviewees were in the shade, in both summer and winter surveys. On sunny days, people were, for the most part, in the shade, a fact that greatly contributes to the acquisition of smaller PET values when compared to those obtained for persons located in the sun. This behavior constitutes an important factor of adaptive comfort.

Table 3 also presents a comparison of the results of this study with the results of the studies conducted by Lin [9] in the city of Taiwan (climate hot and humid) and by Salata et al. [26] in the city of Rome (Mediterranean area). When comparing the results of Lin [9] and Salata et al. [26], we conclude that, despite the different climates, Taiwan and Rome present similar values for Thermal perception - PET “Neutral” interval and for Neutral and Preferred Temperatures. When comparing the results of this study with the results of the study of Lin [9], both conducted in similar climates, we conclude that the range “Neutral” of thermal sensations for Belo Horizonte and for Taiwan have a similar amplitude, of 8 °C and 7.2 °C, respectively. Both intervals, however, are wider than the comfort range determined by Matzarakis et al. [21] for the countries of Central/Western Europe, as mentioned in Section 3.2. The differences between the neutral temperatures and preferred temperatures are smaller for Taiwan than for Belo Horizonte, with preferred temperatures slightly lower than the neutral temperature. For Taiwan, both temperatures, neutral and preferred, both in winter as in summer, are within the comfort range bounded by Lin [9]. In Belo Horizonte, however, with the exception of the preferred temperature in the winter season, all neutral temperatures and the preferred temperature for the summer, are outside the range “Neutral” of thermal sensation. This highlights, as previously mentioned, that people yearn for cooler thermal conditions during the summer and warmer thermal conditions during the winter, reinforcing the findings of Section 3.1. These results also confirm the impact of expectations on the thermal comfort of respondents in Belo Horizonte and supports the theory of “perceptual alliesthesia” as defined by Spagnolo and de Dear [14]. These data also reinforce the evidence of a seasonal difference in thermal neutrality and preference in outdoor areas as suggested by Spagnolo and de Dear [14] and confirmed by Nikolopoulou and Lykoudis for different climatic zones in Europe [8].

4. Conclusions

This article aimed to evaluate thermal comfort conditions of urban open spaces in the Brazilian city of Belo Horizonte and to identify thermal adaptation processes, by analyzing the responses from pedestrians obtained from field surveys conducted during summer and winter, in two public squares of different nature and character.

The results show that, in general, under the same thermal conditions, as far as thermal sensation and thermal comfort is concerned, individuals tend to be more tolerant in *Liberdade* square than in *Sete de Setembro* square, and in winter, rather than in summer. Factors related to psychological adaptation are attributed for such differences. These include the context in which the stimuli occur (naturalness, perceived control, environmental diversity, along with the perception of greater adaptive opportunities), and linked to experience (thermal history on longer timescales - seasonal) were contributing factors for the greater levels of tolerance in *Liberdade* square and in winter, respectively.

Based on data analysis two relevant hyphotheses were formulated; first, that the thermal sensation and the thermal comfort intervals may be slightly different for the same location between seasons; and second, that a comparison between the calibration of the scale for the evaluation of thermal comfort and the calibration of the thermal perception scale would result in a wider “Comfortable” range when compared to the “Neutral” interval.

The calibration of the index PET enabled the definition of the thermal acceptability range; “Cold” for PET values bellow 19 °C; “Neutral” for PET values between 19 °C and 27 °C; and “Hot” for PET values greater than 27 °C.

Thermal preference was assessed by comparing neutral and preferred temperatures, for both summer and winter. The analysis demonstrated that people long for cooler thermal conditions during the summer and for warmer thermal conditions during the winter, indicating that although higher temperatures are expected in the summer leading to higher thermal neutrality, the preference is for lower temperatures, with preferred temperatures for summer and winter, being lower when compared to the comfort range defined. This temperature difference is bigger the higher the air temperature (i.e. summer as opposed to winter), highlighting the impact of the psychological adaptation processes identified – expectations and alliesthesia. Neutral temperature values were

27.7 °C in summer and 15.9 °C in winter; preferred temperature values were 20.9 °C in winter and 14.9 °C in summer.

Behavioral adaptation processes were also identified, such as the variation of the garment in order to adapt to the thermal conditions in winter and the predominance of the location of respondents in the shade in both squares and in both seasons. It was concluded that provision of shade and areas exposed to the wind are important design strategies for Belo Horizonte, since they contribute to cooler thermal conditions.

Design initiatives such as adding more shaded shelters, planting trees and providing more environmental diversity spatially will mitigate the impact of adverse microclimatic conditions, providing the population with increased adaptive opportunities and improving their thermal comfort and overall satisfaction in the city.

The results of this study have a local validity and may not be applicable in different climates and cultural areas without adaptations. They may contribute to the elucidation of issues influencing thermal comfort in urban spaces in Belo Horizonte and similar climatic contexts. The in-depth understanding of these issues will enable further development and adoption of design practices, improving the urban environment and encouraging their public use at different times of the year.

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