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Implications of air-conditioning use on thermal perception in open spaces: A field study in downtown Rio de Janeiro

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ABSTRACT

The interference of thermal history in a person's thermal perception has been explored by several authors and this has been one of the pillars of the concept of adaptive comfort. Given that a general trend towards a more frequent usage and ownership of air-conditioning (AC) units or central systems is taking place worldwide, and considering the fact that AC-users show a diminished tolerance to heat stress when compared to more acclimatized persons, this paper discusses the consequences of AC-usage in climate-responsive urban design. Rio de Janeiro (22° 54′ 10″S, 43° 12′ 27″W) has a tropical climate with summer rains (Aw) and is characterized by frequent heat stress conditions. In such context, air conditioning is a common strategy to reduce indoor heat in buildings. The purpose of this study was to analyze the influence of AC-usage in the thermal perception of a large group of urbanites as regards to Rio's outdoor thermal conditions. Thermal votes were assessed by means of standard questionnaires in several field monitoring campaigns. Meteorological variables, measured on site with a portable weather station were post-processed to UTCI values (*Universal Thermal Climate Index*). Field data showed significant differences among groups of respondents who reported having access to AC-units (or central systems) at home and/or at work in terms of thermal sensation votes. By applying the derived set point UTCI values for two subgroups (AC-users against non users) to Rio de Janeiro's TMY2 (typical meteorological year) data, a significant rise in the annual percentage of heat stress hours was found for AC-users, in magnitude even higher than expected changes in annual heat stress percentages due to climate-responsive urban planning and thus increasing the demands on heat stress mitigation strategies.

1. Introduction

The main motivation of the present research is the definition of optimal thermal conditions for outdoor spaces in Rio de Janeiro. Such delineated “comfort zone for the outdoors” will be further important for future improvements in urban planning and landscaping proposals and thus influence the usage of open spaces. Studies on the thermal perception of local population in outdoor spaces are crucial for a climate-responsive urban planning. A number of studies carried out in the field of outdoor thermal comfort are devoted to the proposition of design tools and guidelines for urban planning. From some of such studies, guidelines for improvement of outdoor spaces are proposed [6,13,22,31,32].

The interference of thermal history in individual thermal perception has been suggested and explored by several authors [2,7,8,10,14,16,26,33,35] and this has been indeed one of the pillars of the concept of adaptive comfort, which lead to the development of ANSI/ASHRAE Standard 55-2010. However, a survey of 26 outdoor thermal comfort field studies over a wide range of climates and geographical locations aimed at providing standards and guidelines for this line of investigation [21] showed an overall lack of questions related to the individual thermal history.

The trend towards a more frequent use and ownership of air-conditioning (AC) units or central system is presently mostly driven by middle-income countries [9], with China as a prime example where sales of air conditioners has nearly doubled over the last 5 years. By drawing a predictive model for AC-usage from

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high-quality data from Mexico, also accounting for end-of-century temperature change projections, Davis and Gertler [9] predicted near-universal saturation of air conditioning in all warm areas within just a few decades. If AC-users are suggested to be less tolerant to heat stress than more acclimatized persons [5], and as the trend towards AC-usage is rising, what are the consequences for urban design?

Assuming that a climate-oriented design of new outdoor spaces or a redesign of existing ones should be strongly dependent on the local population thermal preferences and expectations, a relevant question must be posed: what should the target group be when establishing thermal comfort ranges for outdoor areas? In warm locations where AC-usage is a rising trend, should planners aim at the present population (AC-users and non users, irrespective of their access to AC-units or central air-conditioning systems) or at a saturation level, for AC-users only, assuming an unavoidable AC-usage of nearly 100% in households and offices in the near future? Or aim instead at the local population who does not have access to AC, showing therefore a higher resilience and adaptation to heat stress? What are the consequences of adopting one target group or the other in terms of thermal perception and preference?

According to Koeppen–Geiger's climate classification, Rio de Janeiro (22° 54′ 10″S, 43° 12′ 27″W) has a tropical climate with summer rains (Aw). Annual maximum temperature is on average 27 °C and heat stress characterizes local climate throughout the year. Average maxima during summer lie around 30 °C. In such context, air conditioning is a common strategy to reduce indoor heat –in the present sample of 985 subjects, only about 29% reported having no access to air-conditioned spaces neither during their everyday work activities nor at home. However this figure is subject to change, contingent on improvements in general socio-economic conditions, access to cheaper AC-units and climate change scenarios.

The purpose of this study is to analyze the influence of AC-usage in the thermal perception of a large group of urbanites as regards to outdoor thermal conditions. Thermal votes were assessed by means of standard questionnaires in several field monitoring campaigns in the downtown area of Rio de Janeiro. Meteorological variables, measured on site with a portable weather station were converted to index values with UTCI (*Universal Thermal Climate Index*). UTCI is a non-steady state index based on a multi-node model of human thermoregulation [11] using the approach of equivalent temperature.

2. Method

The monitoring series were carried out along with the administration of standard comfort questionnaires throughout summer periods in 2012–2015. Summer conditions are in this case relevant as they characterize the most typical climatic conditions of Rio de Janeiro and present the most critical challenge to urban planners.

Monitoring campaigns took place at 7 different monitoring points in pedestrian areas with limited vehicle access. The monitoring points were pre-defined for evaluation in respect of urban geometry attributes (narrow streets, proximity to green spaces and urban parks, uniform/non-uniform street canyons, public squares) and are located near historic sites of interest (Fig. 1a). The definition of each point was based on photographic imagery of the surrounding area and on the obtained sky-view factor (SVF). The SVF was obtained from fisheye images taken at 1.10 m above ground, which were post-processed in RayMan [30,36], for each point. Although SVF can be affected by vegetation and thus vary according to the season of the year, in the case of Rio, the colder season does not impact deciduous trees (e.g. with leaf loss) when existent, thus calculated SVF includes adjacent buildings and trees/vegetation. Furthermore, the study is concerned with the summer season, when vegetation is present. The relationship between SVF and local thermal perception is not dealt with in this paper.

For the measurements, a Davis Vantage Pro2 weather station, equipped with temperature and humidity sensors, anemometer cup with wind vane, silicon pyranometer and globe thermometer was employed, which was mounted on a bicycle ('Meteobike') for easy access to each point (Fig. 1b). Resolution and operation range of each piece of equipment are shown in Table 1. In total 18 outdoor survey campaigns took place, typically under clear-sky conditions.

Climatic variables (air temperature and humidity, wind speed and direction, solar radiation and globe temperature) were monitored according to ISO 7726 [18] standards. Each measurement/survey campaign spanned up to five hours (typically from 10am to 3pm, local time). The mean radiant temperature T_{mrt} was calculated according to ISO 7726 [18] for forced convection (Eq. (1)) from the measured globe temperature (T_g), wind speed (V_a), air temperature (T_a), and globe's emissivity (ε_g, assumed 0.95) and diameter (D, approximately 110 mm).

$$Tmrt = \left\{ (Tg + 273)^4 + \left[\frac{(1.1 \times 10^8 \times Va^{0.6})}{(\varepsilon_g \times D^{0.4})} \right] \times (Tg - Ta) \right\}^{\frac{1}{4}} - 273 \quad (1)$$

The comfort questionnaire was aimed at the assessment of the respondents' thermal perception, and was designed according to ISO 7730 [19] symmetrical 7-point two-pole scales. The sample consists of eventual passers-by, which reported a residency in Rio de Janeiro of no less than six months and which were exposed to the outdoors at least for 15 min. Considering the very low probability of finding substantial amount of individuals which were exposed to outdoor conditions for longer periods, particularly when using "volunteers" (passers-by), a residency of at least 15 min outdoors was adopted as a criterion for the "time spent outdoors" factor. This is the minimum space residency recommended by ANSI/ASHRAE Standard 55 [1] for indoor thermal comfort evaluations taking into account the concept of thermal adaptation.

Apart from the perceptual assessment questions (thermal sensation and preference, according to the recommendations of ISO 10551 [17]), demographic questions were also made (gender, age, height, weight) along with questions related to air-conditioning usage in the home and at work and with regard to the neighborhood or district of origin of the interviewee. The clothing insulation was estimated according to a look-up table with typical clothing garments (Table A.1, Annex A, ISO 9920 [20]).

Data quality was ensured by the fact that the weather station was new and the sensors were all factory calibrated. Outliers were controlled in terms of meteorological variables and subjective data (demographic information). Measured ranges were considered to be consistent with the typical conditions for the summer season.

Outdoors thermal conditions were post-processed with the non-steady state Universal Thermal Climate Index (UTCI) by means of BioKlima v. 2.6, which was developed by Blazejczyk (https://www.igipz.pan.pl/Bioklima-zgik.html), with wind speed correction for the height of 10 m as recommended by the operational procedures [3].

3. Results

The summer sample consists of 985 votes covered in the 18 monitoring campaigns. Recorded air temperature ranged 25–37 °C. Table 2 shows the points covered during the summer campaigns with corresponding SVF features. Thermal votes ranged from −1 to +3 in the 7-point assessment scale, with most of the thermal