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Thermal history and its influence on occupants' thermal acceptability and cooling preferences in warm-humid climates: a new desire for comfort?

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Abstract

By the end of the 20th century it became extremely rare for commercial and educational buildings in South America to rely on anything other than air conditioning to create comfort indoors. Apart from the realization of the energy consumption and carbon footprint of such practice, is that occupants' expectations changed considerably. Air conditioning can be associated with a *new desire for comfort*. This project investigates the influence of prior exposure to air conditioning on occupants' thermal acceptability and cooling preferences in mixed-mode University buildings located in warm-humid climate zone in Brazil. Questionnaires were administered while indoor microclimatic measurements were carried out (air temperature, radiant air temperature, air speed and humidity). Results suggest significant differences in occupants' thermal acceptability and cooling preferences based on their thermal history. These findings also indicated that occupant's rising comfort expectations; resulting from constant air conditioning exposure, militate against the implementation of adaptive comfort principles in bioclimatic buildings.

Keywords: thermal history, thermal comfort, cooling preference, mixed mode buildings, energy conservation.

Introduction

After the 1970s oil crises, many countries started to look for ways of improving building energy efficiency. Since HVAC is the single largest energy end use in the built environment, it was inevitable that designers would start to question our dependence on air-conditioning. The spread of air-conditioned environments in the 20^{th} century dramatically altered occupants' expectations and it became extremely rare for commercial and educational buildings in South America to rely on anything other than air conditioning to create comfort indoors.

Since the ultimate success or failure of a building project depends heavily upon the quality of the indoor environment delivered to the building occupants (Ürge-Vorsatz et al. 2007), it is imperative that buildings meet occupants' expectations. With the advent of air conditioning, Ackerman (2002) argues, occupants' expectations have changed. As air-conditioning became embedded in the perceptions and expectations of occupants, technological innovation shifted design responsibility in comfort provision from the architect to mechanical engineer, and control responsibility from the occupant to technology (Roaf et al. 2010).The maintenance of narrow temperature ranges requires significant energy inputs, and it has been established that static environments do not necessarily result in appreciably higher levels of occupant satisfaction(Arens et al. 2009). The current focus is re-awakening an interest in natural ventilation (Tanabe and Kimura, 1989; de Dear and Brager, 2002; Toftum, 2004; Zhang et al. 2007).

There is anecdotal evidence that this desire for comfort could be linked to occupant's thermal history (Kwok, 1998; Chun et al. 2008) and that occupants of air conditioned buildings tended to prefer such buildings, while occupants of non-air conditioned buildings preferred not to have air conditioning (de Dear and Auliciens, 1988; Cândido et al. 2010; Chun et al. 2004; Kim et al. 2011).When combined, these findings suggest that building occupants can become 'addicted' to static environments and it militates against the adaptive model of thermal comfort which advocates the shift from statically controlled indoor environments to passively ventilated buildings occupied by active occupants. But does it also mean that they will present significant differences in terms of thermal preference when the thermal constancy of air conditioning is replaced by the thermal variability that characterizes natural ventilation? If so, would this 'addiction also take place for those occupants whose are constantly exposed to naturally ventilated buildings? This paper focuses on these two questions and investigates the influence of prior exposure to air conditioning on occupants' thermal acceptability and cooling preferences in university buildings located in the Brazilian warm and humid climate zone.

Method

The fundamental feature of this field study design is the proximity in time and space of the indoor climate observations with corresponding comfort questionnaire responses from the occupants of mixed-mode buildings. Four field campaigns were carried-out at classrooms from the Federal University of Santa Catarina. These rooms present a mixed-mode system mainly operated by its occupants, with operable windows; ceiling fans and air-conditioning being the main features in order to modify temperature indoors.

Climate

Florianópolis is an island located on the southern coast of Brazil (latitude 27°40'S) and according to Köppen's classification it presents a humid subtropical climate(see Figure 1). The mean monthly temperatures vary from 21 to 29°C during summer time and from 13 and 22°C during winter (Goulart et al. 1998). Relative humidity is high throughout the year (around 82%) and there is no dry season. The highest rainfall occurs from January to March and the lowest from July to August (mean annual precipitation is 1521mm).

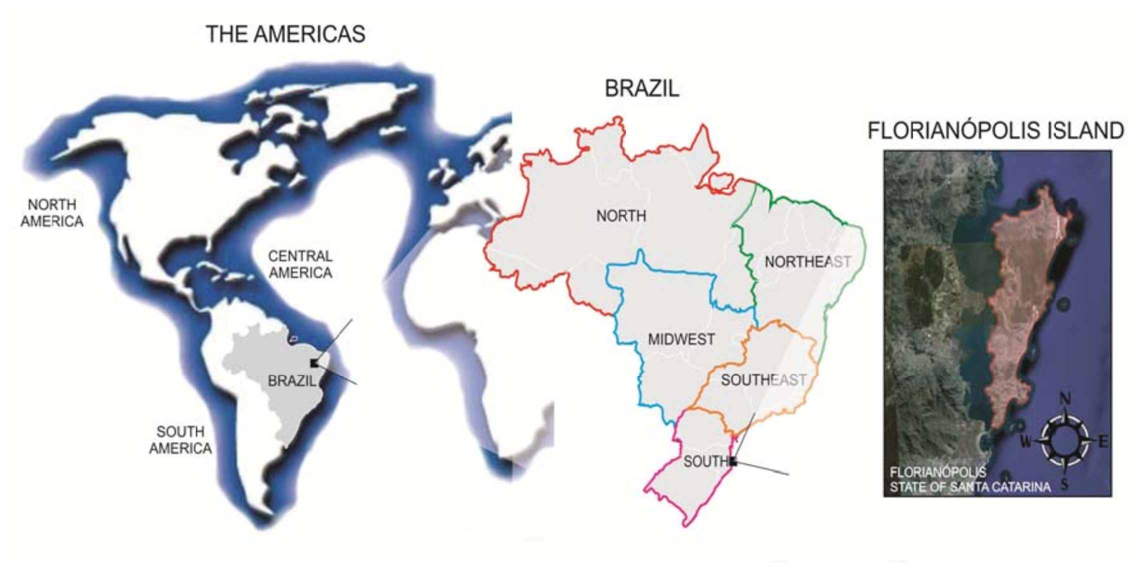


Figure 1. Location of Florianópolis city, Brazil.

Table 1 shows the mean outdoor temperature during the field study. This information was provided by the Laboratory of Energy Conversion Engineering and Energy Technology (LEPTEN/UFSC) from its meteorological station located at campus. This station provides data to the World Meteorological Organization (WMO**)**.

Table 1. Outdoor meteorological conditions measured during the days of the experiment.

	Min.	Max.	Mean (°C)	SD
March	16.9	27.4	22.9	3.2
May	16.3	26.1	20.7	2.6
April	16.6	23.7	20.4	2.7
November	18.5	22.8	21.5	1.1

Subjects

A total of 2292 questionnaires were collected during the field study, from 544 students. Table 2 depicts subjects' anthropometric information and Figure 2 shows subjects' gender percentages.

Occupants wore typical university clothing ensembles varying from 0.22 to 0.89 *clo* (these values include 0.01 *clo* estimated for student's desk, which contributes an additional insulation according with ISO 7730, annex C). During the survey, students performed sedentary activities ($70W/m^2$). Insulation and Activities level were estimated based in ISO 7730 (2005).

Table 2. Subjects' anthropometric information.

	Min.	Max.	Mean	SD
Age (years)	21	47	21.2	3.4
Weight (Kg)	40	116	65.7	12.4
Heigh (m)	1.50	1.95	1.72	0.1

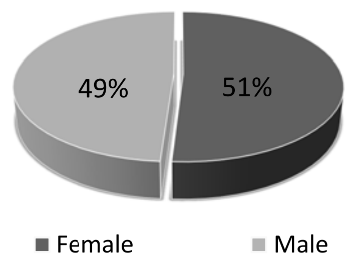


Figure 2. Subjects' gender distribution.

Questionnaires

The 'right-here-right-now' questionnaires focused on subjects' whole-body thermal comfort, acceptability, and subject's prior exposure to air-conditioning, cooling and air movement preferences. The questionnaire was presented in four parts:

(i) Subject's anthropometric information and activities;
(ii) Subjects' cooling preferences, including air-conditioning, natural ventilation only and natural ventilation combined with fans. This also presented questions about subjects' prior exposure to air-conditioning, including where they are exposed to air-conditioning (car, home and/or work) and approximately duration of this exposure per day(h);
(iii) Thermal sensation and acceptability.
(iv) Air movement preferences and acceptability.

Indoor microclimatic instrumentation and measurements protocol

Air temperature, humidity, globe temperature and air speed were registered with laboratory precision using a microclimatic station (globe thermometer, psychrometer for dry and wet-bulb temperatures and a hot wire anemometer) located at the centre of the occupied zone at 0.60m from the floor(see Figure 3).

Individualized air speed values were also measured using a handheld hot-wire anemometer sensor in order to measure air movement around the subjects. Figure 3 shows this sensor fixed on a support that allowed taking air speed measurements at the subjects working height (0.60m) without any disturbance from the researcher's body.

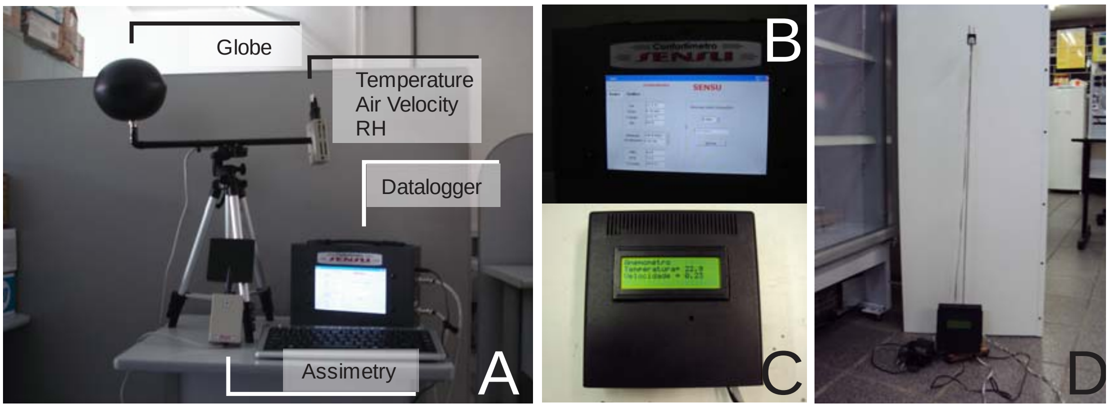


Figure 3. Microclimatic Station (A), Datalogger's detail (B), Anemometer's data display (C), and Handheld hot-wire anemometer(D).

Complementary measurements were taken with the handheld hot-wire anemometer in order to measure air speed from fans and air conditioning. During these measurements, windows were kept closed, ceiling fans were turned on and air conditioning was turned on (Figure 4) or off (Figure 5).

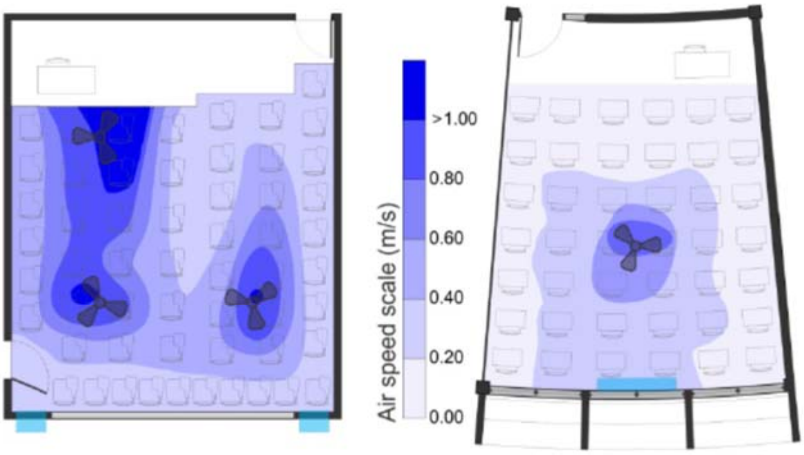


Figure 4. Air speed mapping representation when air conditioning was turned on.

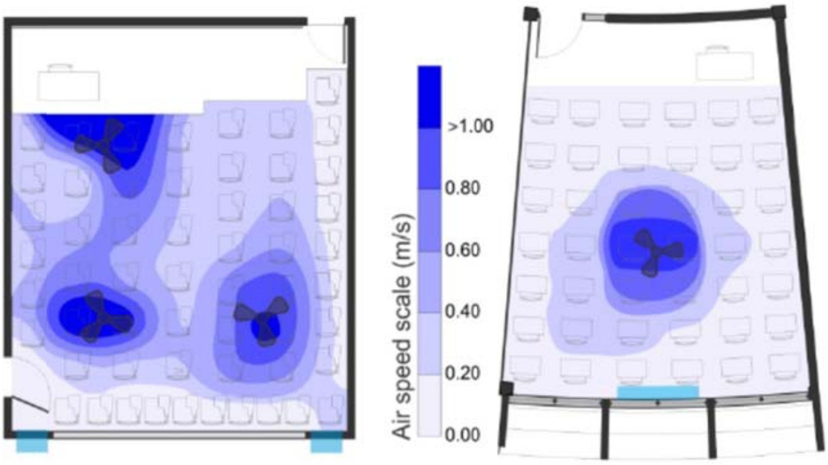


Figure 5. Air speed mapping representation when air conditioning was turned off.

Subjects assessed their immediate indoor environment via a 'right-here-right-now' questionnaire four times within a 140 minute period (20 minutes intervals). Subjects only started answering the questionnaire after 30minutes after their arrival in order to avoid any influence from their exposure to thermal transients. This period was also used to set-up the indoor microclimatic station and to explain the questionnaire and procedure to the subjects. Figure 6 presents a schematic representation of this protocol.

Subjects' activities were not influenced deliberately by the researchers during the survey and they were allowed to freely adapt their clothing and cooling devices accessible to them (turning on and off air-conditioning and fans). Windows remained closed throughout the survey, simulating the typical use of the room during warm days. Students were not allowed to leave the room during the experiments.

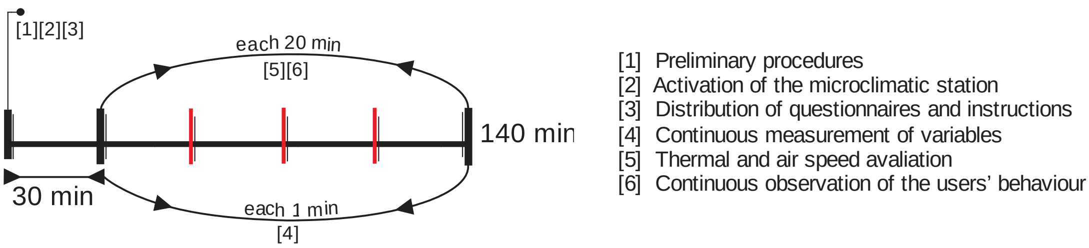


Figure 6. Measurement protocol schematic representation.

Data analysis and statistical tests

Analysis of variance (ANOVA) and ***t-test*** were used when conducting statistical tests, with significance level of $P < 0.05$.The final database was organized on Microsoft Excel®, a proprietary commercial spreadsheet application distributed by Microsoft Corporation. The values were merged with a range of calculated indices using the WinComf software package of Fountain and Huizenga (1996). These indices include Mean Radiant Temperature (MRT), Operative Temperature and Standard Effective Temperature (SET). The graphics and analysis were based on the SET index, a thermophysiological model based on ASHRAE's extended research and practice, which is defined as "*the equivalent dry bulb temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for activity concerned, would have the same heat stress (skin temperature) and thermo-regulatory strain (skin wittedness) as in the actual test environment*" (Gagge et al. 1986; McIntyre, 1980).

Results and Discussion

Subjects were divided into two groups based on their previous exposure to air-conditioning (AC) indoor environments. Figure 7 shows that split between these two groups is nearly the same, with 47% of subjects not being constantly exposed to air-conditioning and 53% being exposed to static indoor environments during their daily activities.

Subjects were also asked about the duration of their exposure to air-conditioning on average per day. Figure 8 shows that most of this exposure took place at work (4.5 hours per day, on average), followed by the time that subjects spent using AC at home (4.4 hours) and inside their cars (1.3 hours).

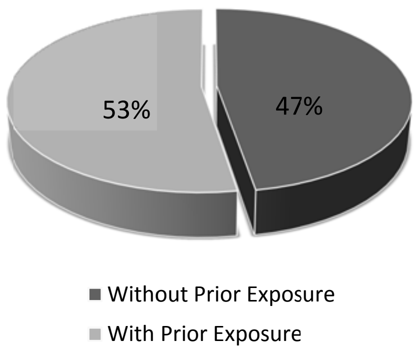


Figure 7. Subjects prior exposure to air conditioning.

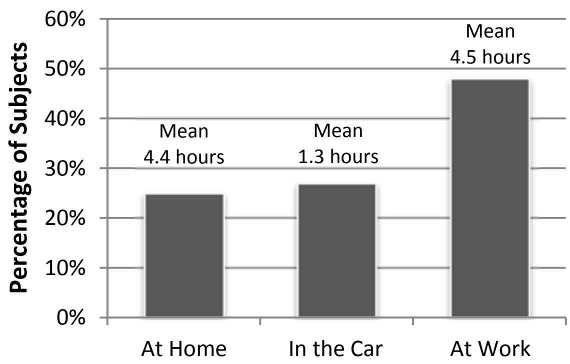


Figure 8. Location and duration of exposure to air conditioning.

Figure 9 shows the observed trigging temperature for air conditioning during the field studies. Throughout the field studies period, subjects turned on the air conditioning during the survey on eight occasions. For each one of this occurrence, the mean standard temperature was calculated based on the twenty minutes exposure prior to subjects effectively turning the device on. Figure 9 also shows the mean outdoor temperature for each occurrence. From this figure, it is possible to infer that subjects were turning air-conditioning on with SET varying from 21.1 to 24.2°C, with 22.5°C being the average trigging temperature.

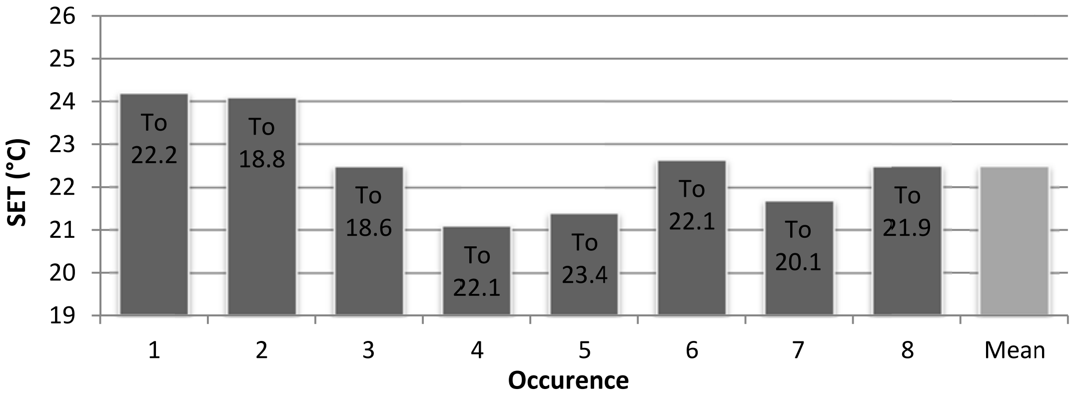


Figure 9. Observed trigging temperatures for air conditioning.

Figure 10 shows subjects's thermal sensation votes sorted by SET values varying from 19to 26°C. No significant differencewas found based on subjects'exposure to AC. For both groups, thermal sensation was concentrated within the three middle categories of the seven point scale: 'slightly warm', 'neutral' and'slightly cool'. Subjects voting for these three catergories on the thermal sensation scale consistently changed when SET values increased and this behaviour was the same for both groups in the study (with and without exposure to AC).

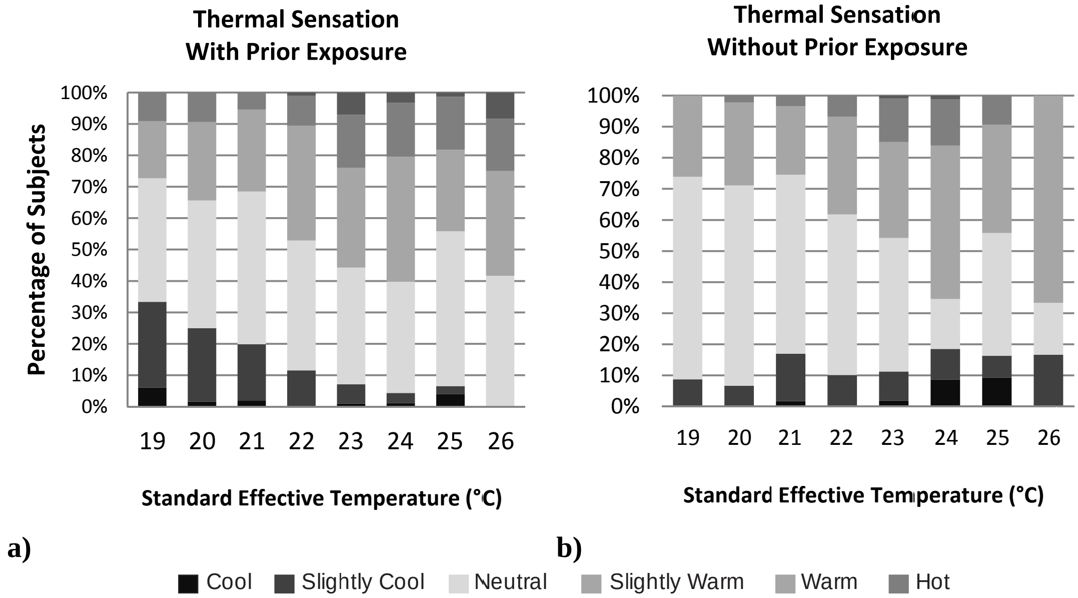


Figure 10. Subjects overall thermal sensation votes for those with (a) and without prior exposure (b).

In contrast with thermal sensation votes, thermal acceptability presented a significant difference based on subjects' exposure to AC and these results can be seen on Figure 11. Subjects exposed to AC presented less tolerance to warmers temperatures, with their thermal acceptability decreasing consistently when SET increased from 19 to 25°C. For this group, the biggest difference in thermal acceptability can be identified for SET values of 25 and 26°C (see Figure 11 a); when the percentages of subjects' considering their indoor environment as 'unacceptable' reached 30 and 65%, respectively. Subjects not exposed to AC also presented decrease on their thermal acceptability votes once SET increased, see Figure 11b. However the percentage of subjects classifying their indoor environment as 'unacceptable' was below 30% for SET temperatures of 25 and

26°C. These values are considerably inferior when compared to those found for occupants with exposure to AC. Observing both the Figures 11a and 11b, it is clear that the prior exposure makes its occupants to become increasingly intolerable with respect to higher temperatures.

Thermal preference votes shaded some light into these values showing that the occupants' who considering their environment "unacceptable" voted mostly to a cooler environment in both groups (see Figure 12). The difference between the group who are exposed to AC and the group who are not, is the subjects' number that wants a cooler environment (26% more) or preferred no changes (16% less) respectively, with complements the assertion of the preceding paragraph. The "want warmer" votes only show up in the group that is not exposed to AC environments, corresponding to 10% of the votes (Figure 12b).

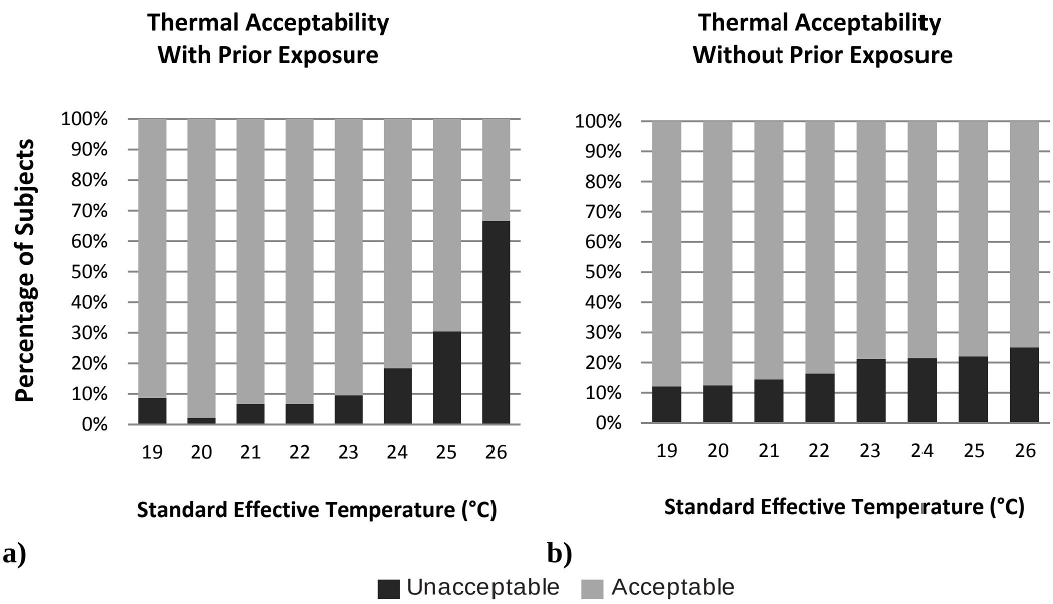


Figure 11. Occupants' thermal acceptability votes distribution for subjects (a) with and (b) without prior exposure to air conditioning.

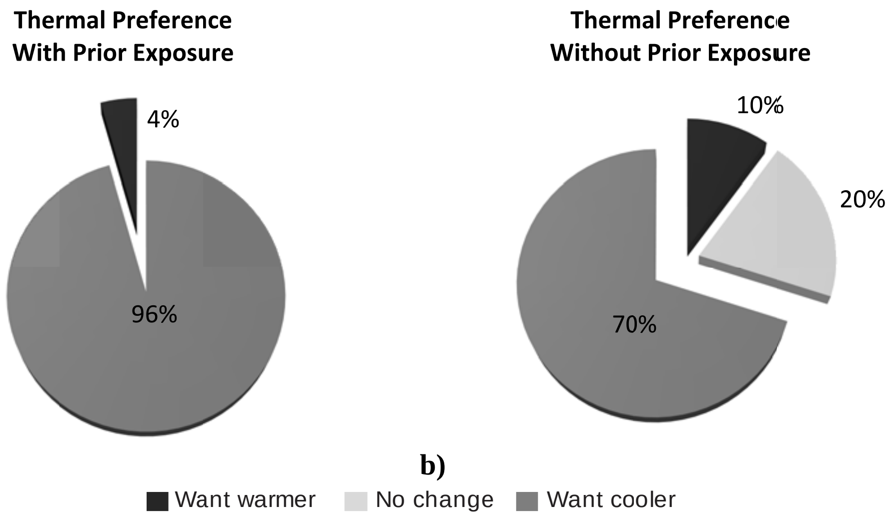


Figure 12. Occupants' thermal preference for those voting as "unacceptable" for their thermal acceptability. Subjects with (a) and without(b) prior exposure to air-conditioning.

When subjects were asked about their cooling preferences at particular moments in time, pronounced differences were found between the two groups of analysis. The majority of subjects exposed to AC (54%) voted for ‘air-conditioning’ as their cooling preference (see Figure 13 a). For this same group, only 20% preferred ‘natural ventilation’ and 26% voted for the combination of ‘natural ventilation and fans’. Figure 13b shows percentages for cooling preferences for subjects without exposure to AC. For this group, the majority of subjects indicated ‘natural ventilation’ (48%) as their cooling strategy of choice. Approximately 28% preferred the combination of ‘natural ventilation and fans’ and only a minority of 24% of subjects declared ‘air-conditioning’ as their preferred cooling strategy at the moment of the survey. These results are consistent with the experiments of Cândido et al. (2010), and reinforce the “thermal history” factor on subjects’ preferences.

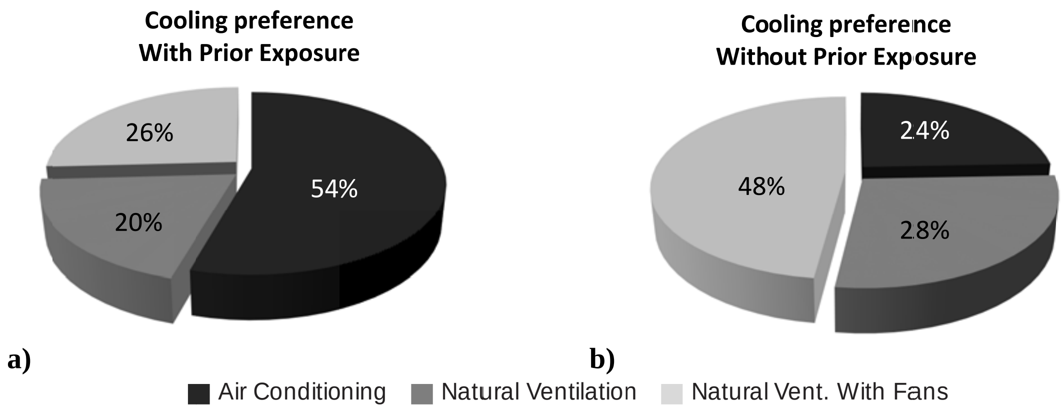


Figure 13. Cooling preferences for subjects (a) with and 9b) without prior exposure to air conditioning.

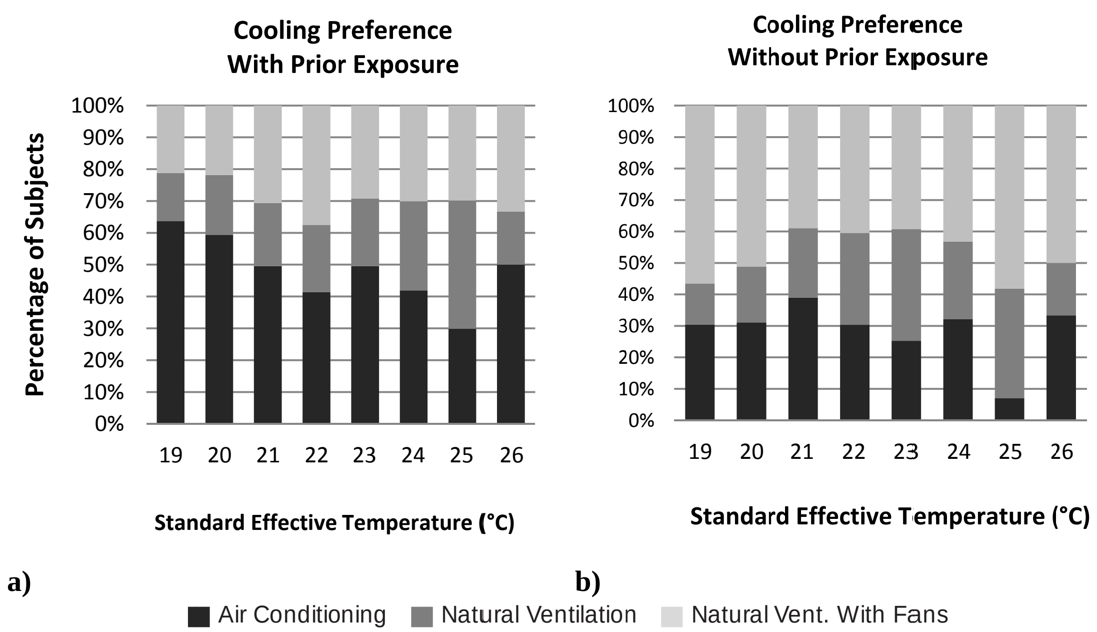


Figure 14. Occupants’ cooling preferences sorted by SET for those subjects (a) with and (b) without prior exposure to air conditioning.

Marked gender differences were found when analyzing subject’s cooling preferences and these results can be found on Figure 15. Male subjects indicating AC as their cooling preference was significantly higher than female subjects. Female subjects indicated 'natural ventilation' or 'natural ventilation in combination with fans' on most of occasions. Such 'rejection' to air-conditioning from females found in this study supports previous findings by Choi et al. (2010), where females subjects were mostly dissatisfied under mild temperatures when compared to males (about 18 – 22°C).

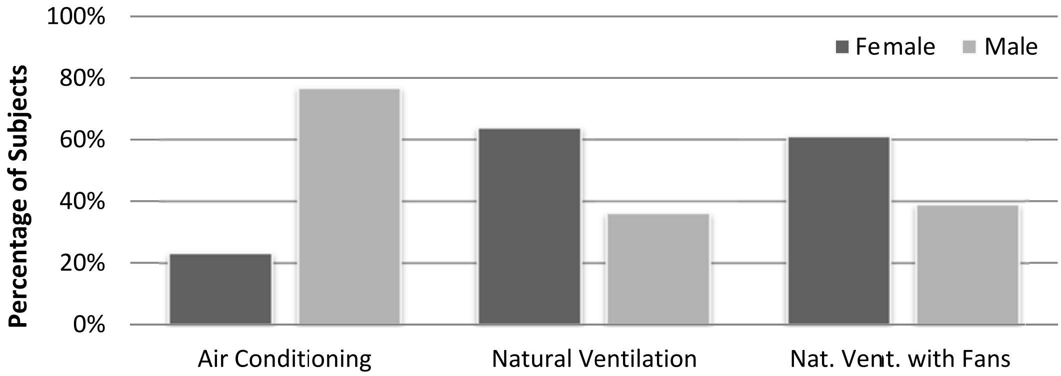


Figure 15. Occupants' cooling preferences binned by gender.

Figure 16 shows that for this project results followed the same pattern from Parsons (2002) under neutral to cold conditions, with female's subject being more susceptible to felling 'cold'. However, under hot conditions, a higher frequency of male votes was recorded, which is more consistent with the studies from Indraganti and Rao (2010).These results support previous findings in which similar differences were found between male and female subjects(Breslin, 1995; Webb and Parsons, 1997; Parsons, 2002).

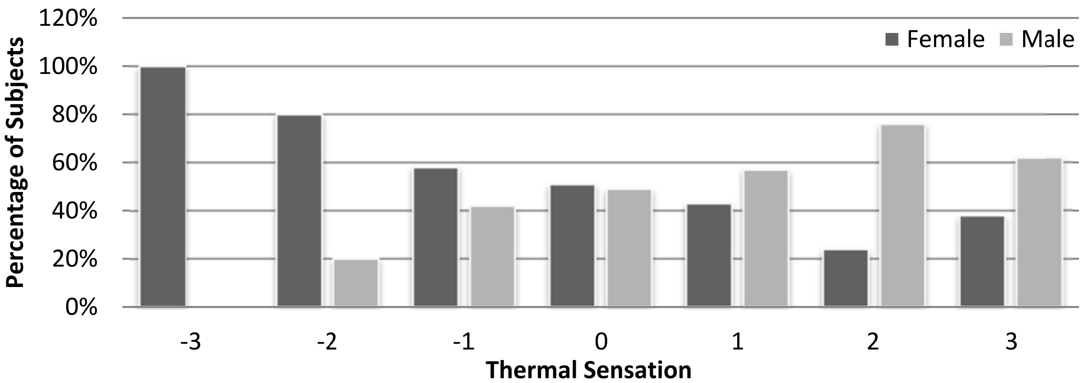
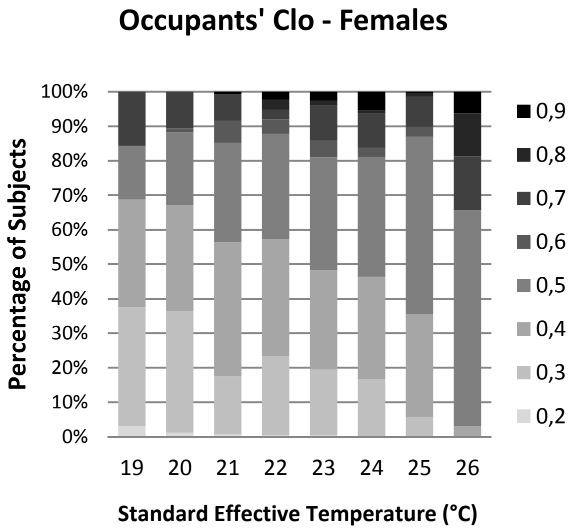
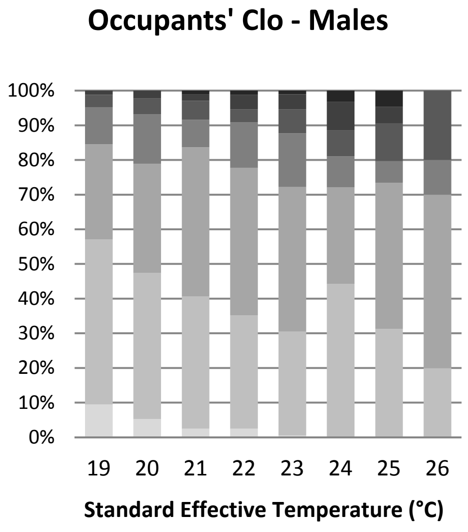


Figure 16. Thermal sensation votes from females and males.

As pointed out by Morgan and de Dear (2003), significant differences in *clo* values based on gender were also found in this study and these results are summarized on Figure 17. Female's *clo* values were slightly higher than males across all SET values, suggesting that female subjects were more likely to adapt their clothing. Male subjects however presented more constant *clo* values regardless of SET increments.





a) **b)**

Figure 17. Occupants' *clo* values sorted by different SET for (a) female and (b) male subjects.

Conclusions

This paper presented the connection between prior exposure to air-conditioning spaces and the possible implications on occupant's thermal preferences and acceptability. Occupants' prior exposure to air conditioning influenced their overall thermal comfort expectations and cooling preferences. Such influence wouldn't be revealed solely based on occupants' thermal sensation votes, since no significant differences were found between subjects with and without prior exposure to air conditioning. Additionally, significant differences related to subjects' thermal sensation and cooling preferences were found between male and females, showing that males are more susceptive to prefer AC systems than female subjects. This may occur because females preferred significantly higher room temperatures than males.

These findings also indicated that occupants' rising comfort expectations; resulting from constant exposure to air conditioning indoor environments, militate against the implementation of adaptive comfort principles in bioclimatic buildings and the return to more naturally ventilated buildings. Whether such air conditioning saturation would be reversible is yet to be understood and more research is necessary in order to shed some light on how 'acclimatize'such 'air-conditioning addicts' to warmer indoor environments without compromising their thermal acceptability.

New research tackling such questions should be discusses and could heavily contribute to closing the gap in knowledge between occupants' expectations and the built environment. The opportunities to higher set-points in air-conditioning buildings are feasible and must be encouraged, like the Cool Biz campaign, being a good early step to contribute to a better energy management within the built environment.

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