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Influence of environmental variables on thermal comfort and air quality perception in office buildings in the humid subtropical climate zone of Brazil

Candi Citadini de Oliveira [a], Ricardo Forgiarini Rupp [a,b], Enedir Ghisi [a]

[a] Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópolis/SC, Brazil
[b] Technical University of Denmark, Department of Civil Engineering, International Centre for Indoor Environment and Energy, Kgs. Lyngby, Denmark

Abstract

This study evaluates the influence of environmental variables on users' thermal comfort and air quality perception in the humid subtropical climate of Florianópolis, southern Brazil. A building with central air-conditioning system and three mixed-mode buildings, which alternated between natural ventilation and air-conditioning modes, were investigated. Statistical analyses were performed considering environmental data collected *in situ* between 2014 and 2016 – using microclimate stations, a portable thermo-anemometer and a CO_2 analyser – and users' subjective responses obtained by means of an electronic questionnaire. Results showed a direct influence of air temperature and humidity ratio and indirect influence of air movement on thermal comfort. In addition, thermal, air movement and humidity sensation, preference and acceptability affected thermal comfort and air quality perception, highlighting the importance of carrying out a complete assessment of users' perception of the thermal environment. This work supports the use of the ASHRAE 55 adaptive thermal comfort model for mixed-mode buildings under natural ventilation operation. Based on the results obtained in this study, the use of hybrid ventilation strategy is recommended for energy savings due to reducing the use of air-conditioning and improving indoor air quality as there is a decrease in air pollutants level.

Keywords: air temperature; air movement; humidity ratio; carbon dioxide (CO_2); mixed-mode buildings.

1 Introduction

In Brazil, the energy consumption in the commercial sector corresponds to 14.3% of the total electricity demand [1]. In these buildings, the use of air-conditioning represents 30% to 40% of the total energy consumption, mainly because of the maintenance of constant temperature indoors, regardless of weather or season [2]. In addition, artificially conditioned buildings may be related to thermal comfort and air quality problems due to the lack of control of environmental conditions by users or the inefficiency of air-conditioning system – in maintaining acceptable levels of air humidity and pollutants, for example. Thus, it is important to rethink the use of air-conditioning in the current scenario of buildings.

As the global concern to minimise environmental impacts by reducing the consumption of energy and natural resources increases, it is crucial to search for strategies that provide good use of available resources. Energy-efficient strategies, such as natural ventilation and fans, mitigate the impact of air-conditioning use and reduce buildings energy demand. Also, these alternatives improve thermal comfort and indoor air quality in buildings due to air movement and air exchange, especially in hot or subtropical climates [3-9].

Since people spend up to 90% of their time indoors [10-12], it is important to study users' thermal comfort and air quality perception in buildings as they can positively or negatively influence occupants' satisfaction, performance and health [13,14]. Many studies have investigated the influence of environmental variables on thermal comfort and indoor air quality. For example, suitable air speed and humidity values have the potential for energy savings because of the expansion of the acceptable range of indoor temperature [3-6,15-17]. Thus, satisfactory air speed and humidity conditions keep occupants comfortable, due to the intensification of convection and evaporation processes in the body, increasing heat losses to the environment in hot climates [15-20].

Numerous authors have identified users' preference for high air speed in situations with high air temperature and humidity [4,6,17,21-23], demonstrating the importance of air movement for thermal comfort in hot climates. In some studies, there was a reduction in warm sensation by increasing air speed for temperatures up to 30ºC [17,24], 32ºC [20] or 34°C [4]. For higher temperatures, the use of air-conditioning was recommended. The influence of air speed on air movement perception was also observed [21,25].

At high temperatures, research shows that elevated relative humidity values are generally related to greater warm sensation and thermal discomfort, and lower thermal acceptability [18,24,26]. In contrast, other works have found no relationship between these variables [22,27,28]. There is also a discrepancy in results regarding the influence of air humidity on humidity subjective variables in field studies since some authors have identified a significant relationship between these variables [15,16,25] and others have not [29]. It is noteworthy that users' insensitivity to high air humidity values may be related to people's acclimatisation to the local environmental conditions [26,28].

In general, studies verified that high air temperature and humidity tend to worsen the perceived air quality, while an increase in air movement significantly improves air quality satisfaction [9,17]. Research in naturally ventilated classrooms identified a strong correlation between humidity and CO_2 concentration since people exhale water vapour and carbon dioxide [30]. Greater variations in CO_2 concentration were observed in mixed-mode buildings, reaching higher levels compared to buildings with central air-conditioning system [31]. Besides, different results were obtained about the relationship between users' thermal comfort and air quality perception indoors, indicating a strong or weak correlation between these variables [32,33].

Most studies on thermal comfort and air quality have been carried out in Europe, Asia and North America. Thus, the scarcity of analyses involving both thermal comfort and air quality in Brazil is noteworthy, so more studies are required in the country. In this context, the overall objective of this study is to analyse how environmental variables affect users' perception in office buildings located in the humid subtropical climate of Florianópolis, southern Brazil. Specifically, this paper aims (1) to understand the environmental conditions to which users were subjected in order to be in thermal comfort or discomfort, (2) to conduct a relevant and unprecedented direct analysis involving air quality and thermal comfort in the humid subtropical climate, (3) to analyse the use of the adaptive thermal comfort model to mixed-mode buildings under natural ventilation operation, and (4) to raise awareness about the role of the mixed-mode strategy to reduce energy consumption in buildings while maintaining or improving the thermal comfort and air quality levels.

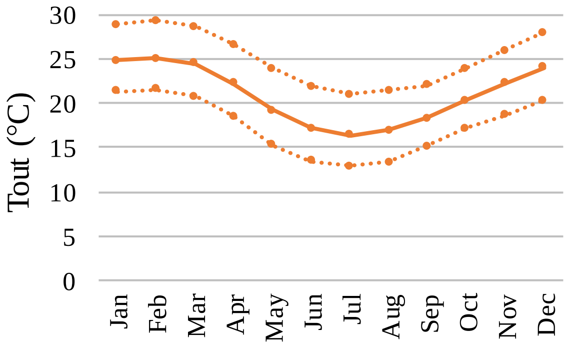
2 Method

This work is based on analyses of data collected during two years in four office buildings located in Florianópolis, Brazil. One building with central air-conditioning system (ACB) and three mixed-mode buildings (MMB1, MMB2 and MMB3), in which users could switch between natural ventilation mode (NV) and air-conditioning mode (AC), were analysed. In all buildings, occupants performed sedentary activities related to public administrative work in their workstations.

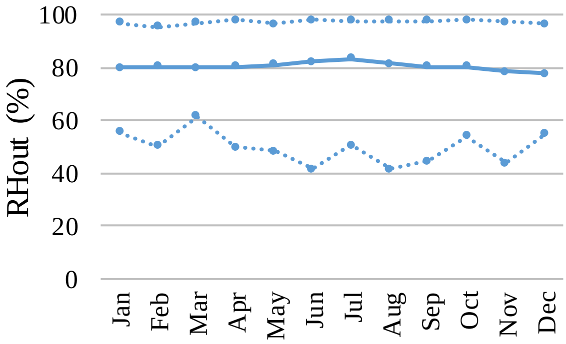
2.1 Florianópolis climate

The city of Florianópolis is located in southern Brazil (latitude: -27°36’, longitude: -48°33’ and altitude: 7m). The climate is classified as humid subtropical, with hot summers and mild winters. The annual mean outdoor air temperature is 20.9ºC, with a mean temperature of 16.4°C in the coldest month (July) and 25.1°C in the hottest month of the year (February). The municipality is situated mostly on an island in the Atlantic Ocean (Fig. 1). The annual mean outdoor relative humidity is 80.4%, ranging from 41.3% to 98.0% during the year. In Florianópolis, precipitation occurs throughout the year, with a mean annual rainfall of approximately 1700 mm and absence of a dry season. The city has four well-defined seasons, with the possibility of sudden changes in weather conditions due to cold fronts coming from polar air masses. The minimum, mean and maximum outdoor air temperature and outdoor relative humidity can be seen in Fig. 2.

Fig. 1: Florianópolis Island, highlighting buildings location
Source: Google Earth Pro [34]



(a) Outdoor air temperature



(b) Outdoor relative humidity

Fig. 2: Minimum, mean and maximum air temperature and relative humidity in Florianópolis
Source: Climatological Standards (1981-2010) [35]

2.2 Data contextualisation and statistical analyses

For measurements of internal environmental variables, microclimate stations were used to record air temperature, globe temperature, air speed and relative humidity at five-minute intervals. A portable thermo-anemometer and a CO_2 analyser were also used for instantaneous measurements (Table 1). Simultaneously, subjective data were obtained by means of an electronic questionnaire applied to users every twenty minutes for five times during a work shift. The questionnaire contained general questions about users' anthropometric and demographic characteristics and questions regarding their thermal, air movement, air humidity and air quality perception. Field data collection occurred over several days between March 2014 and March 2016 and covered the four seasons, which included diversified environmental characteristics that better represent the climatic conditions of Florianópolis throughout the year. More information about field data collection can be found in the study carried out by Rupp *et al.* (2018), which used part of the database of this study [36].

Table 1: Details of the instruments used in the field study

Instruments	Parameters measured	Range	Accuracy
Microclimate stations	Air temperature (°C)	0 – 60	± 0.2
	Globe temperature (°C)	0 – 60	± 0.2
	Air speed (m/s)	0 – 3	± 3%
	Relative humidity (%)	5 – 96	± 3%
Portable thermo-anemometer	Air temperature (°C)	0 – 80	± 1.0
	Air speed (m/s)	0 – 20	± 3%
CO_2 analyser	CO_2 (ppm)	0 – 10000	± 75

In order to assess the relationship between environmental and subjective variables, statistical analyses were performed such as linear regressions, correlations, bar charts and boxplots. For this purpose, each user subjective response was combined with the corresponding environmental conditions. This study considered the absolute humidity for the analyses involving humidity, as suggested by some authors [28,37,38], since the relative humidity is associated with air temperature. According to ISO 7726:1998 [39], absolute humidity can be calculated based on the measurements of air temperature and relative humidity, being expressed through the partial pressure of water vapour or the humidity ratio. As the partial pressure of water vapour and the humidity ratio have a relation and the latter is used more frequently in psychrometric charts, the analyses performed herein involving humidity were based only on humidity ratio.

Table 2 presents the parameters and corresponding scales, *i.e.* questions and answers in the questionnaire. The variables considered are: thermal sensation (TS), thermal preference (TP), thermal acceptability (TA), thermal comfort (TC), air movement sensation (AMS), air movement preference (AMP), air movement acceptability (AMA), air humidity sensation (AHS), air humidity preference (AHP), air humidity acceptability (AHA) and air quality satisfaction (AQS). For users who considered the air quality unsatisfactory, the following problems were assessed: "Air is stuffy", "Air is not clean" and "Air is odorous". These variables have a seven-point scale, from -3 ("It is a big problem") to +3 ("It is a small problem"), with the extra option "Not" ("It is not a problem").

Table 2: Parameters and corresponding scales considered in the questionnaire

Parameters	Scales	
Thermal sensation	+3	Hot
	+2	Warm
	+1	Slightly warm
	0	Neutral
	-1	Slightly cool
	-2	Cool
	-3	Cold
Thermal preference	+1	Cooler
	0	No change
	-1	Warmer
Thermal acceptability	+1	Unacceptable
	0	Acceptable
Thermal comfort	+1	Uncomfortable
	0	Comfortable
Air movement sensation	+2	Very low air movement
	+1	Low air movement
	0	Enough air movement
	-1	High air movement
	-2	Very high air movement
Air movement preference	+1	More air movement
	0	No change
	-1	Less air movement
Air movement acceptability	+1	Unacceptable
	0	Acceptable
Humidity sensation*	+3	Very wet
	+2	Wet
	+1	Slightly wet
	0	Neutral
	-1	Slightly dry
	-2	Dry
	-3	Very dry
Humidity preference*	+1	Less humidity
	0	No change
	-1	More humidity
Humidity acceptability*	+1	Unacceptable
	0	Acceptable
Air quality satisfaction	+3	Very satisfied
	+2	Satisfied
	+1	Slightly satisfied
	0	Neutral
	-1	Slightly unsatisfied
	-2	Unsatisfied
	-3	Very unsatisfied

* The questions regarding humidity perception had the extra option “I do not know how to answer”.

3 Results and discussion

In order to investigate the influence of air temperature, air speed, air humidity and CO_2 concentration on thermal comfort and air quality perception of users of office buildings located in Florianópolis, Brazil, the relationships between these variables were analysed.

3.1 Overview of the data

Collected data consist of 7564 measurements of environmental variables linked to subjective data: 1567 in building MMB1, 3321 in MMB2, 582 in MMB3, and 2094 in ACB. In total, 45% of the responses to the electronic questionnaire were from women and 55% from men. In this work, data from actual buildings were considered and, therefore, there was no uniform distribution of environmental data. Although it was difficult to carry out some analyses due to the small number of observations in some cases, data collection in existing buildings allows a more faithful representation of reality regarding environmental variables variations and the complexity of the real environment where the users are.

Tables 3 to 5 show the mean and standard deviation of environmental, subjective and occupant-related variables for each building and operation mode. The environmental variables considered in this study were: air temperature (Ta), mean daily outdoor air temperature (Tout), air speed (Va), relative humidity (RH), mean daily outdoor relative humidity (RHout) and humidity ratio (Wa) (Table 3). In general, the mean air temperature, air speed and outdoor relative humidity remained similar for all buildings and operation modes. Otherwise, the mean outdoor air temperature was lower for mixed-mode buildings during natural ventilation operation, indicating that natural ventilation was mainly used during the intermediate seasons (autumn and spring) and winter. About relative humidity and humidity ratio, higher values were observed for natural ventilation mode compared to air-conditioning mode. This result can be explained by air humidity reduction due to the use of air-conditioners [15,40].

All subjective variables means were close to zero, indicating a predominance of neutral thermal sensation and thermal preference for no change (Table 4). There was a slight tendency for users to consider low air movement sensation and preference for more air movement, in all buildings and operation modes. Also, there was a slight tendency towards wet ambient sensation in mixed-mode buildings in natural ventilation mode and dry ambient sensation in buildings operating with air-conditioning. No data was collected regarding humidity subjective variables in building MMB3. In this way, mixed-mode buildings provide similar thermal environment perceptions compared to buildings fully air-conditioned. Therefore, the use of hybrid ventilation strategy can save energy by reducing the use of air-conditioning [7]. In addition, there was a correspondence between thermal, air movement and humidity sensation and preference mean values in most cases – for example, warm sensation and preference for a cooler environment. Similarly, other authors have identified a correspondence between the mean humidity sensation and humidity preference [15,25].

Regarding occupant-related variables (Table 5), there was a great similarity between the mean values of users' age, weight, height, BMI (Body Mass Index) and metabolic activity in all buildings and operation modes. However, there was a significant difference in clothing insulation mean between the two operation modes in mixed-mode buildings, being higher for natural ventilation. This confirms the predominance of the use of natural ventilation in intermediate seasons and winter. It is noteworthy that none of the buildings had an artificial heating system.

Table 3: Environmental variables according to building and operation mode

Variables (mean ± S.D.)	MMB1		MMB2		MMB3		ACB
	NV n=952	AC n=615	NV n=1712	AC n=1609	NV n=457	AC n=125	AC n=2094
Ta (°C)	22.6 ± 2.0	24.1 ± 1.4	23.9 ± 1.3	24.1 ± 1.2	24.0 ± 1.3	23.9 ± 1.0	23.4 ± 0.8
Tout (°C)	18.3 ± 2.8	25.1 ± 2.3	19.3 ± 2.0	23.6 ± 3.4	19.5 ± 1.1	20.2 ± 1.6	21.6 ± 3.1
Va (m/s)	0.13 ± 0.05	0.14 ± 0.09	0.12 ± 0.08	0.12 ± 0.02	0.16 ± 0.07	0.20 ± 0.04	0.12 ± 0.06
RH (%)	65 ± 8	56 ± 10	67 ± 9	60 ± 6	61 ± 10	54 ± 5	62 ± 8
RHout (%)	78 ± 7	77 ± 5	83 ± 6	81 ± 6	76 ± 6	78 ± 5	75 ± 8
Wa (g/kg)	9.39 ± 1.55	8.77 ± 1.68	10.20 ± 1.52	9.22 ± 1.11	9.41 ± 1.50	8.28 ± 1.00	9.23 ± 1.33

Table 4: Subjective variables according to building and operation mode

Variables (mean ± S.D.)	MMB1		MMB2		MMB3		ACB
	NV n=952	AC n=615	NV n=1712	AC n=1609	NV n=457	AC n=125	AC n=2094
TS	-0.02 ± 0.69	-0.15 ± 0.77	0.05 ± 0.75	0.02 ± 0.77	0.15 ± 0.93	-0.02 ± 0.73	-0.19 ± 0.77
TP	-0.03 ± 0.48	-0.03 ± 0.54	0.08 ± 0.52	0.07 ± 0.54	0.06 ± 0.54	0.01 ± 0.48	-0.02 ± 0.55
AMS	0.30 ± 0.58	0.12 ± 0.66	0.25 ± 0.62	0.14 ± 0.69	0.37 ± 0.69	0.11 ± 0.44	0.17 ± 0.66
AMP	0.15 ± 0.44	0.04 ± 0.49	0.16 ± 0.50	0.09 ± 0.47	0.19 ± 0.50	0.07 ± 0.46	0.06 ± 0.49
AHS	0.19 ± 0.73	-0.22 ± 0.77	0.26 ± 0.94	-0.25 ± 0.84	–	–	-0.27 ± 0.73
AHP	-0.03 ± 0.31	-0.13 ± 0.44	0.12 ± 0.52	-0.08 ± 0.43	–	–	-0.17 ± 0.45

Table 5: Occupant-related variables according to building and operation mode

Variables (mean ± S.D.)	MMB1		MMB2		MMB3		ACB
	NV n=952	AC n=615	NV n=1712	AC n=1609	NV n=457	AC n=125	AC n=2094
Age (years)	41 ± 10	39 ± 10	38 ± 11	36 ± 11	40 ± 11	37 ± 11	40 ± 11
Weight (kg)	74 ± 16	75 ± 17	73 ± 15	75 ± 16	72 ± 15	74 ± 15	75 ± 15
Height (m)	1.70 ± 0.09	1.72 ± 0.09	1.69 ± 0.10	1.70 ± 0.10	1.67 ± 0.09	1.69 ± 0.07	1.72 ± 0.09
BMI (kg/m²)	25.6 ± 4.1	25.2 ± 5.35	25.2 ± 3.8	25.7 ± 4.0	25.7 ± 4.4	25.9 ± 4.3	25.3 ± 3.7
Clothing insulation (clo)	0.80 ± 0.25	0.57 ± 0.10	0.74 ± 0.19	0.61 ± 0.11	0.70 ± 0.18	0.65 ± 0.15	0.66 ± 0.14
Metabolic activity (met)	1.1 ± 0.1	1.1 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.0 ± 0.1	1.0 ± 0.0	1.1 ± 0.1

In buildings MMB1 and MMB2 there was a predominant use of air-conditioning in summer and natural ventilation in other seasons. In building MMB3, data were collected only in winter, when natural ventilation (78.5%) was used more than air-conditioning (21.5%). Building ACB operated only with air-conditioning and data were gathered during the four seasons. Thus, data collected through all seasons were considered in this research, as well as in works [24,28]. However, most of the studies investigating thermal comfort, especially in hot and humid climates, generally used data gathered only in summer [16,17,19,27,29].

3.2 Compliance with ASHRAE 55

ASHRAE 55-2017 [41] presents two procedures for assessing thermal comfort in buildings based on analytical and adaptive thermal comfort theories. Originally, the standard allowed only naturally ventilated buildings without air-conditioning system installed to be evaluated using the adaptive model of thermal comfort. For other building ventilation types, thus comprising mixed-mode buildings, the analytical model should be used. This ASHRAE 55 requirement for mixed-mode buildings was considered conservative, and research has shown that the adaptive model can be applied to the natural ventilation mode in mixed-mode buildings [42,43]. Recently, the Addendum f to ASHRAE 55-2017 [44] removed the prohibition against applying the adaptive model in spaces that have an air-conditioning system installed but not operating. Thus, the adaptive thermal comfort model can be used for naturally ventilated spaces without mechanical cooling or heating system in operation.

3.2.1 Assessing all buildings according to the analytical model

ASHRAE 55-2017 [41] introduces some methods for determining the acceptable thermal environment in occupied spaces. In this work, the "Elevated Air Speed Comfort Zone Method" was used for situations with air speed higher than 0.2 m/s (n=254). In general, users had no control over air movement, except for some users (n=15) who used portable fans during the field studies. For other situations with air speed not exceeding 0.2 m/s (n=7310), the "Analytical Comfort Zone Method" was used. The analyses were performed using the CBE Thermal Comfort Tool [45]. According to ASHRAE 55, compliance is achieved with PMV (Predicted Mean Vote) values between -0.5 and +0.5.

Table 6 shows a comparison between predicted and actual thermal acceptability and thermal comfort for each building ventilation type. A clear discrepancy can be observed between the values obtained according to ASHRAE 55 and users' perception. Therefore, in the Brazilian subtropical climate, the narrow limits imposed by the standard are not justified even in buildings fully air-conditioned and, if adopted, would lead to high energy consumption.

Table 6: Compliance comparison between ASHRAE 55 and users' subjective responses

Ventilation type	Comply with ASHRAE 55?		Thermal acceptability		Thermal comfort	
	Yes n=4577	No n=2987	Acceptable n=7088	Unacceptable n=414	Comfortable n=6555	Uncomfortable n=946
Mixed-mode NV	62.7%	37.3%	95.7%	4.3%	89.5%	10.5%
Mixed-mode AC	65.2%	34.8%	92.8%	7.2%	84.1%	15.9%
ACB	52.0%	48.0%	94.5%	5.5%	87.9%	12.1%

3.2.2 Assessing mixed-mode buildings during natural ventilation operation

In order to assess the applicability of the adaptive model for buildings with air-conditioning installed but not operating, Fig. 3 shows the indoor operative temperatures against the prevailing mean outdoor air temperature for mixed-mode buildings operating with natural ventilation. It can be seen that indoor operative temperatures varied according to the prevailing mean outdoor air temperature, *i.e.* the relationship between indoors and outdoors is clear. For the 80% and 90% acceptability limits from ASHRAE 55, 98.7% and 93.7% of indoor operative temperatures were within the acceptable limits, respectively. The predicted thermal acceptability from the adaptive model was similar to the actual users' thermal acceptability (Table 6). In this way, this work supports the use of the adaptive model of thermal comfort for mixed-mode buildings under natural ventilation operation in the subtropical climate. Therefore, this result reinforces the importance of the new consideration of the Addendum f to ASHRAE 55-2017 [44], with no evidence that only naturally ventilated buildings should be considered in the adaptive model.

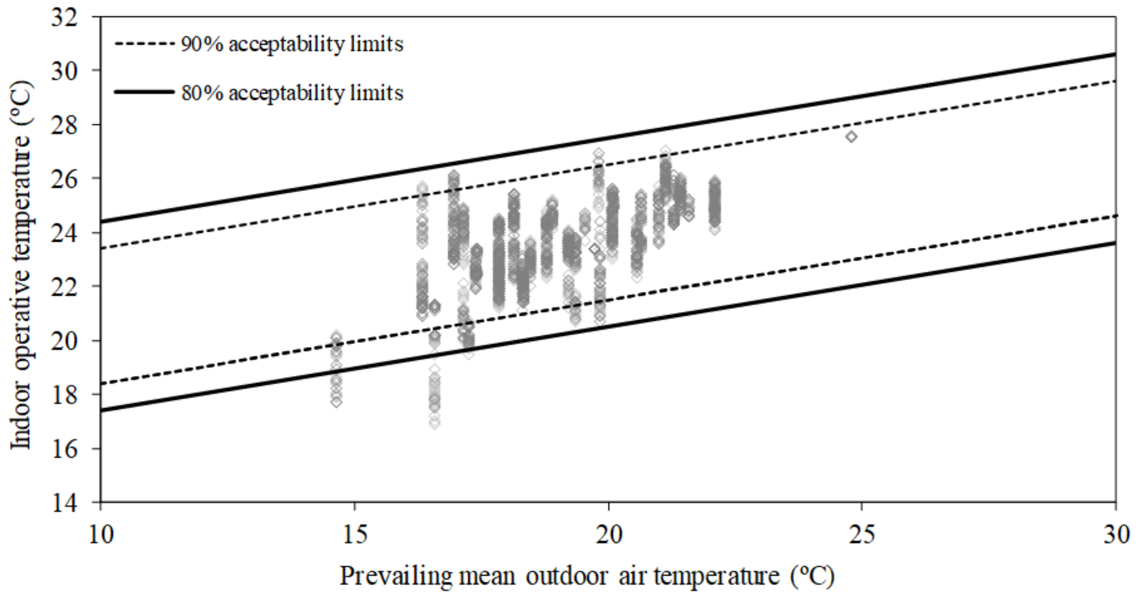


Fig. 3: Indoor operative temperature under natural ventilation operation in mixed-mode buildings plotted on the adaptive model from ASHRAE 55 (n=3121)

3.3 Environmental variables vs. Subjective responses

3.3.1 Air temperature, air movement and air humidity

Linear regressions were performed between the environmental variables air temperature, air speed and humidity ratio and the thermal sensation, in addition to the sensation and preference of air movement and humidity, according to the building ventilation type (Table 7). In the analyses involving humidity perception, the answer "I do not know how to answer" was not included. As expected, an increase in air temperature tended to increase the thermal sensation and preference (statistical significance with $p<0.001$), *i.e.* users felt warm and preferred a cooler environment. These relationships were more evident for mixed-mode buildings under natural ventilation mode and less evident for the building with central air-conditioning system. However, the correlations between air temperature and thermal subjective variables were weak ($R^2 \leq 0.11$).

In general, regressions between air speed and subjective variables were non-significant in mixed-mode buildings during natural ventilation operation and the building fully air-conditioned ($p>0.05$). Mixed-mode buildings in air-conditioning mode had very weak correlations ($R^2 \leq 0.01$), but significant. In this case, an increase in air speed caused lower thermal sensation and preference, in addition to high air movement sensation and preference for low air movement, as expected. Thus, users of mixed-mode buildings may be more sensitive to air movement fluctuations when operating the air-conditioning.

For all building ventilation types, there was a very weak correlation between the humidity ratio and thermal sensation and preference ($R^2 \leq 0.02$), however significant ($p<0.001$). So, an increase in humidity ratio tended to slightly increase warm sensation and preference for a cooler environment. Moreover, regressions between the humidity ratio and humidity sensation and preference were not significant ($p>0.05$). Other studies had also found little influence of relative humidity on thermal sensation [22] and absence of correlation between absolute humidity and humidity subjective votes [29]. This small effect of humidity on subjective variables may be related to users' acclimatisation to high humidity in the region. Other authors pointed out this justification by identifying users' lower sensitivity to environmental variations due to prolonged exposure to high humidity [26,28].

Thus, there was a great difference between the perception of distinct people regarding the effects of air temperature, air speed and air humidity. This could be explained by other factors' influence on users' subjective responses, such as individual characteristics, previous exposure to air-conditioning, sound and lighting conditions, among others.

Table 7: Linear regression equation and coefficient of determination for correlations between environmental and subjective variables

Variables	Mixed-mode NV (n=3105)		Mixed-mode AC (n=2318)		ACB (n=2080)	
	Equation	R^2	Equation	R^2	Equation	R^2
Ta x TS	TS = 0.16Ta - 3.63 [a]	0.11	TS = 0.15Ta - 3.61 [a]	0.06	TS = 0.12Ta - 2.95 [a]	0.02
Ta x TP	TP = 0.09Ta - 2.01 [a]	0.08	TP = 0.10Ta - 2.34 [a]	0.05	TP = 0.11Ta - 2.57 [a]	0.03
Va x TS	p>0.05 [d]	0.00	TS = -0.97Va + 0.09 [b]	0.00	p>0.05 [d]	0.00
Va x TP	p>0.05 [d]	0.00	TP = -0.48Va + 0.09 [c]	0.00	p>0.05 [d]	0.00
Va x AMS	p>0.05 [d]	0.00	AMS = -0.87Va + 0.23 [a]	0.01	AMS = 0.93Va + 0.06 [a]	0.01
Va x AMP	p>0.05 [d]	0.00	AMP = -0.42Va + 0.12 [c]	0.00	p>0.05 [d]	0.00
Wa x TS	TS = 0.06Wa - 0.59 [a]	0.02	TS = 0.07Wa - 0.67 [a]	0.01	TS = 0.06Wa - 0.77 [a]	0.01
Wa x TP	TP = 0.04Wa - 0.35 [a]	0.02	TP = 0.05Wa - 0.40 [a]	0.01	TP = 0.06Wa - 0.54 [a]	0.02
Wa x AHS	p>0.05 [d]	0.00	p>0.05 [d]	0.00	p>0.05 [d]	0.00
Wa x AHP	p>0.05 [d]	0.00	p>0.05 [d]	0.00	p>0.05 [d]	0.00

[a] Statistical significant with p<0.001.
[b] Statistical significant with p<0.01.
[c] Statistical significant with p<0.05.
[d] Statistical non-significant with p>0.05.

Thermal acceptability was analysed as a function of air movement acceptability for each building ventilation type (Fig. 4). The subjective variables' scales correspond to the answer options available in the questionnaires applied to the users. In general, thermal acceptability was high when air movement was considered acceptable and low when air movement was unacceptable. For mixed-mode buildings under natural ventilation mode, thermal acceptability was lower when air movement was considered low. Otherwise, in buildings operating with air-conditioning, thermal acceptability was lower when the air movement was considered high. Therefore, it is notable that thermal acceptability was related to air movement acceptability.

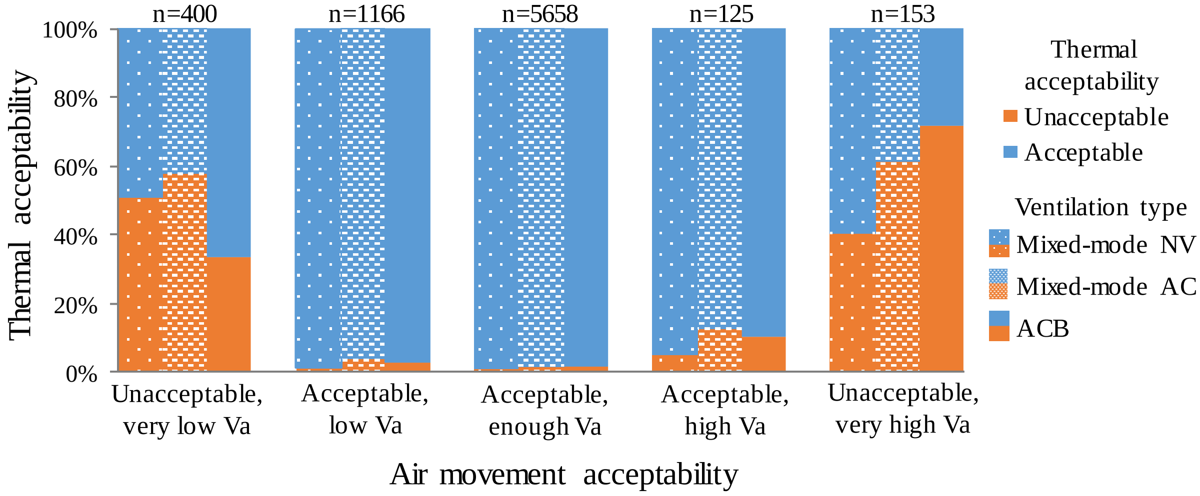


Fig. 4: Thermal acceptability as a function of air movement acceptability for each building ventilation type

3.3.2 Air quality perception

Figs. 5 and 6 show boxplots relating the environmental variables air temperature and humidity ratio with air quality satisfaction, according to the season. Minimum and maximum values, quartiles (1st and 3rd), means and medians are shown. Data from all buildings were considered and, because of the high concentration of low air speed, it was not possible to carry out this analysis between air speed and air quality satisfaction. In summer and winter, there was a tendency to reduce the mean air quality satisfaction as increased the air temperature, while in intermediate seasons there was an oscillation of mean values between 0 and +1. In addition, the mean air quality satisfaction tended to decrease with an increase in the humidity ratio up to 9 g/kg and increased after this value in the summer. In other seasons, the mean values oscillated between -1 and +2. Despite these trends, in all cases at least 50% of the data indicated votes of neutrality or satisfaction with air quality. Furthermore, even for high air temperature and humidity ratio, the mean votes indicated neutrality or satisfaction with air quality, for all seasons. It is noteworthy that regressions between environmental variables and air quality satisfaction were significant for air temperature ($p<0.001$) and non-significant for humidity ratio ($p>0.05$).

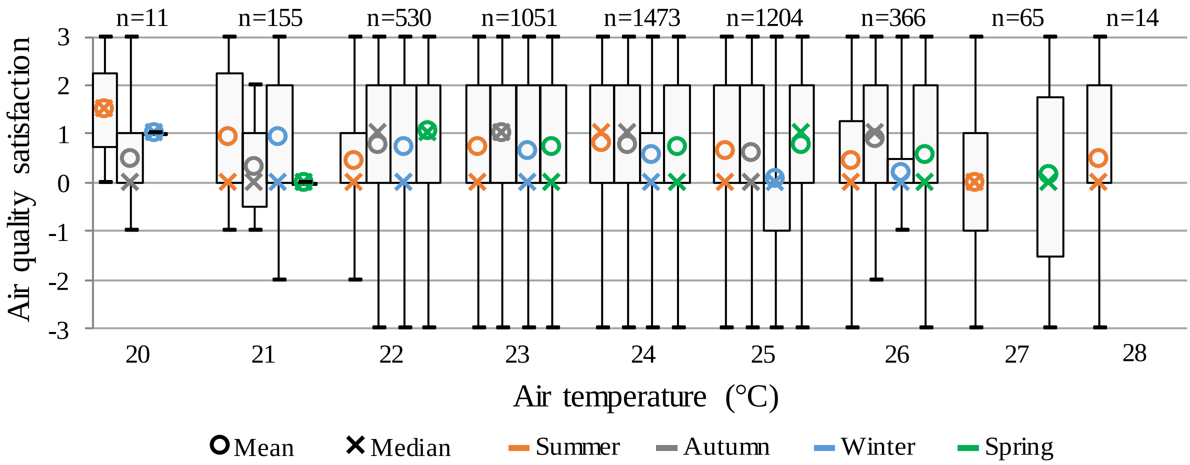


Fig. 5: Boxplot relating air temperature with air quality satisfaction, according to the season

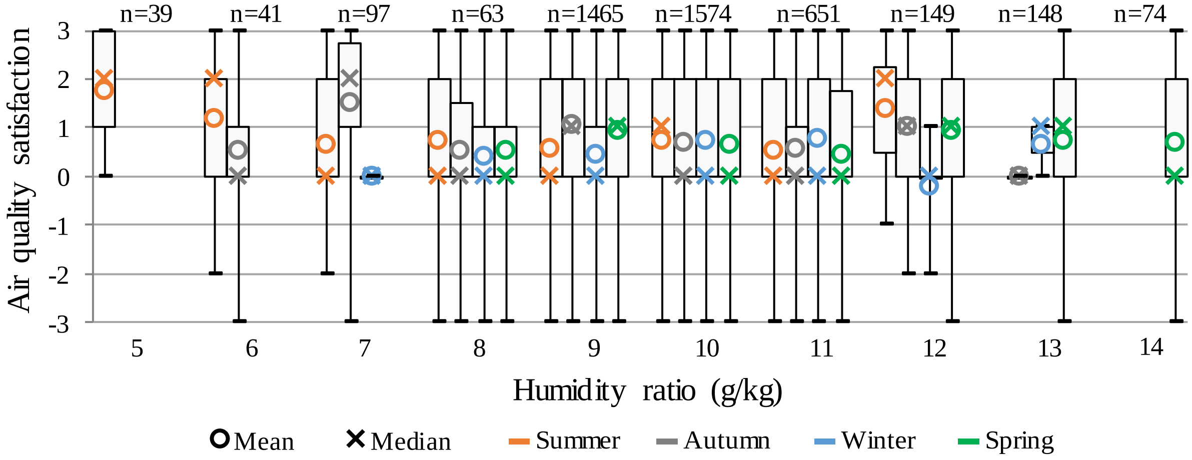


Fig. 6: Boxplot relating humidity ratio with air quality satisfaction, according to the season

Figs. 7 to 9 present boxplots relating thermal, air movement and humidity sensation with air quality satisfaction, according to the season. In general, air quality satisfaction tended to be higher for neutral votes of thermal, air movement and humidity sensation, and lower for extreme subjective votes. For sensation votes between -1 and +1, the mean air quality satisfaction varied between 0 and +2, with at least 50% of users feeling neutral or satisfied with the air quality. Otherwise, there was a predominance of air quality dissatisfaction for extreme votes of thermal sensation, air movement and humidity – especially when the environment was considered warm, with low air movement and humid. However, there was no influence of seasons on the relationship between variables, since the mean air quality satisfaction for each subjective vote was similar between the four seasons. Regressions between the subjective variables and air quality satisfaction were significant for thermal and air movement sensation ($p<0.001$), but non-significant for humidity sensation ($p>0.05$). Thus, there was a significant influence of subjective variables – mainly thermal and air movement sensation – on air quality perception.

It is noteworthy that in Figs. 5 to 9 there are small sample sizes towards the end of the x-axes. Thus, these extreme intervals are not representative and the results must be carefully analysed.

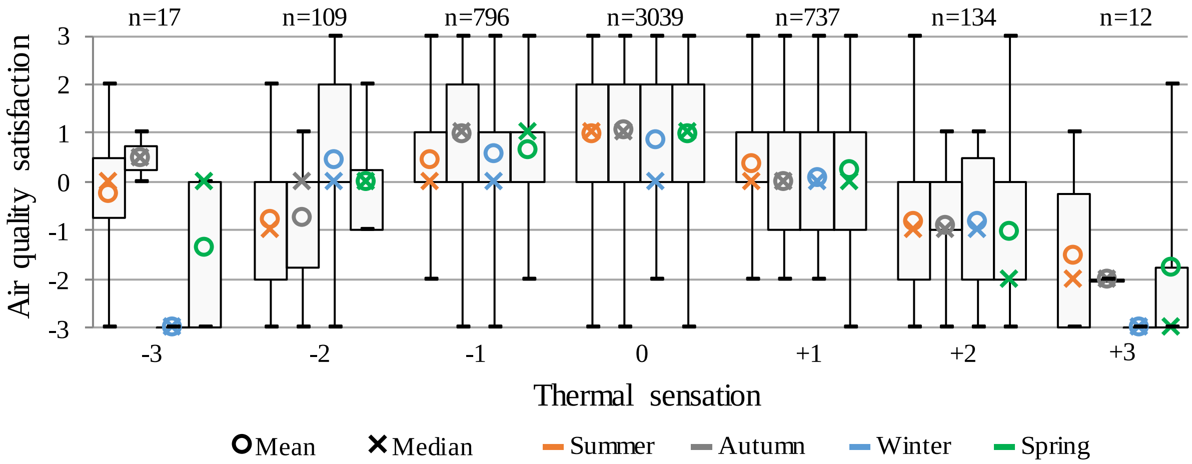


Fig. 7: Boxplot relating thermal sensation with air quality satisfaction, according to the season

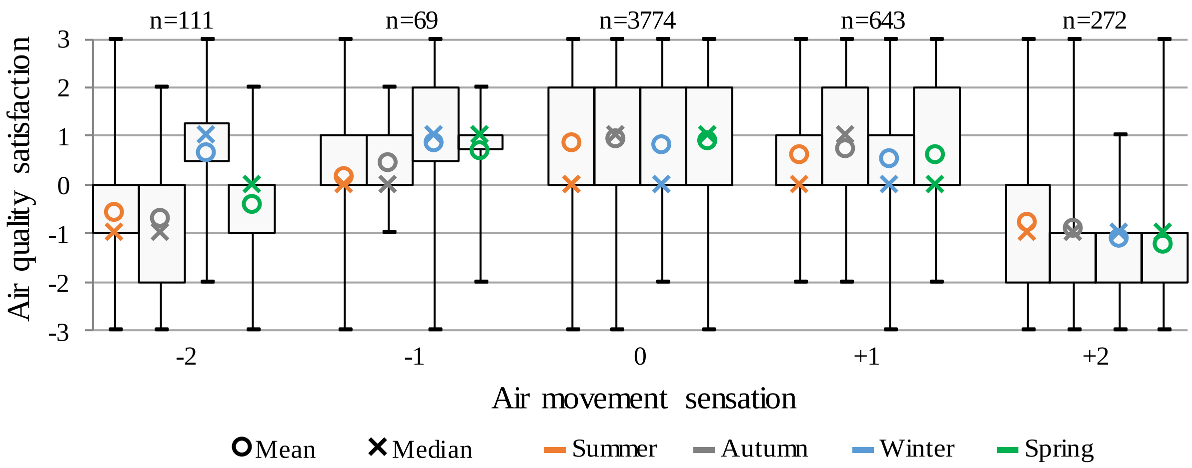


Fig. 8: Boxplot relating air movement sensation with air quality satisfaction, according to the season

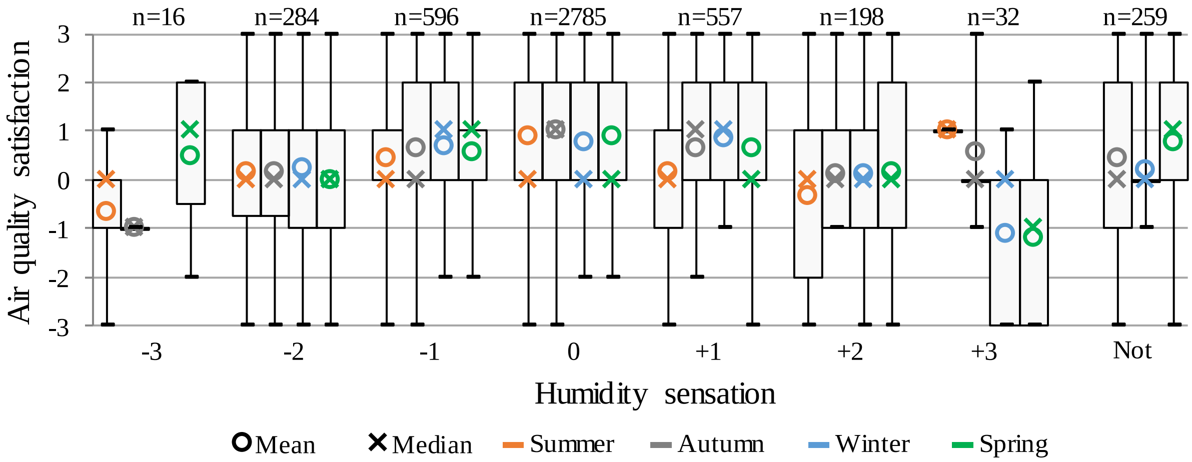


Fig. 9: Boxplot relating humidity sensation with air quality satisfaction, according to the season

The carbon dioxide (CO_2) concentration indoors, measured in parts per million (ppm), was collected in a reduced sample in buildings MMB1, MMB2 and ACB. CO_2 concentration varied between 300 and 900 ppm in natural ventilation mode and 400 and 1300 ppm in air-conditioning mode in mixed-mode buildings, and between 400 and 800 ppm in the building with central air-conditioning system. Higher mean and standard deviation values were verified for mixed-mode buildings in air-conditioning mode (801 ± 213 ppm) compared to the natural ventilation mode (481 ± 117 ppm) and the building fully air-conditioned (621 ± 77 ppm). Similar findings were obtained by [31]. In mixed-mode buildings operating with split air-conditioners with air recirculation, CO_2 exceeded the recommended limit of 1000 ppm established by ANVISA Resolution 09/2003 [46] in Brazil. Contrarily, in the building with central air-conditioning system, CO_2 remained below the recommended limit due to an air exchange system. Based on this, the implementation of an air exchange device in split air-conditioners used in mixed-mode buildings is extremely important.

Fig. 10 shows air quality satisfaction and thermal comfort as a function of CO_2 concentration in addition to the mean air temperature and humidity ratio. CO_2 intervals with less than ten observations were not considered. At high CO_2 levels, there was a higher percentage of neutral votes, decreased air quality satisfaction and absence of air quality dissatisfaction. An increase in CO_2 concentration was related to a reduction in mean humidity ratio and increase in thermal comfort, indicating that higher CO_2 concentrations occurred when air-conditioners were turned on. Thus, the lack of air quality dissatisfaction may be related to high thermal comfort, even for high CO_2 levels. It is noteworthy that CO_2 mean was higher for users satisfied or neutral with air quality (667 ± 224 ppm) compared to dissatisfied occupants (583 ± 155 ppm). This result confirms that users felt more satisfied or neutral for being in thermal comfort, and not due to higher CO_2 levels. In addition, all building ventilation types showed non-significant relationships ($p>0.05$) between CO_2 concentration and air quality satisfaction. Therefore, air quality perception was influenced by factors other than CO_2 level.

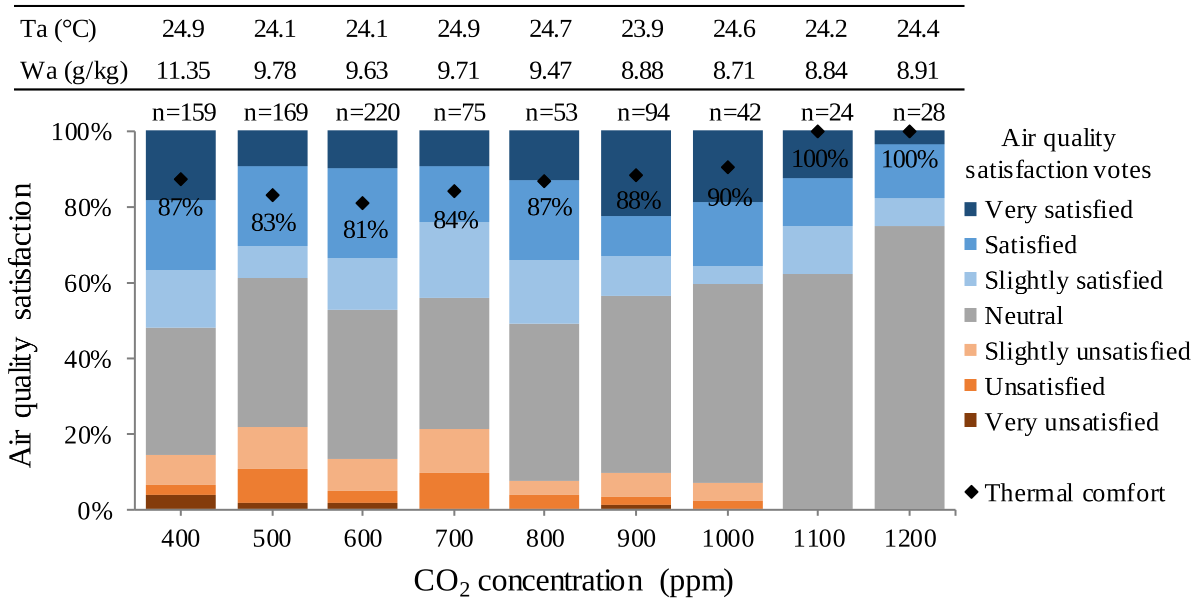


Fig. 10: Air quality satisfaction and thermal comfort as a function of CO_2 concentration. The mean air temperature and humidity ratio are shown above each CO_2 concentration interval

3.3.3 Thermal comfort and discomfort

In general, all buildings showed high thermal comfort, greater than 80% (Table 6). Higher air temperature and humidity ratio means and similar air speed mean were obtained for users in thermal discomfort compared to those in thermal comfort. Moreover, greater sensations of warm, low air movement and humid environment were related to higher temperature and humidity values, without a considerable difference in air speed. Tables S1 to S4 (in the Supplementary data) show the mean and standard deviation of environmental variables, distribution of thermal, air movement and humidity sensation, preference and acceptability votes and distribution of air quality satisfaction and air quality problems votes according to building ventilation type, for users in thermal comfort and discomfort.

Fig. 11 shows the frequency of thermal, air movement and humidity sensation votes for each building ventilation type for users in thermal comfort and thermal discomfort. In all buildings, users in thermal comfort felt predominantly neutral or slightly warm/cool and preferred no change in the environmental conditions, as expected. For users in thermal discomfort, there was a prevailing percentage of slightly warm/cool or warm/cool sensation and preference for colder or warmer environment. Even for users in thermal discomfort, there was a very low percentage of votes indicating hot/cold sensation, less than 5% for all cases. For thermal discomfort condition, the percentage of users preferring a cooler environment was higher than warmer environment in mixed-mode buildings, while the opposite occurred in the building with central air-conditioning system. In addition, thermal acceptability was close to 100%

when users were in thermal comfort and around 55% to 65% when they were in thermal discomfort (Tables S1 and S2, in the Supplementary data). It is interesting to note this distinction between the subjective variables, because, even in thermal discomfort, more than half of the occupants accepted the thermal environment conditions. It is noteworthy that users in mixed-mode buildings under natural ventilation mode were more likely to accept the thermal environment compared to the conditions in which the air-conditioning operated. This result is consistent with the adaptive thermal comfort theory, which states that occupants are more tolerant in environments with natural ventilation. Because of the findings, this study highlights the importance of including a full assessment of users' thermal perception, including questions about thermal sensation, preference, acceptability and comfort in field studies – and not only one question about occupants' thermal sensation, from which thermal comfort condition is inferred.

Users in thermal comfort considered the air movement predominantly enough or low and preferred no change or more air movement. On the other hand, there was a more uniform data distribution for occupants in thermal discomfort, with a significant percentage of very low air movement and preference for more air movement. This occurred mainly in mixed-mode buildings during natural ventilation operation, with 36.2% of very low air movement sensation and 56.4% of more air movement preference. Meanwhile, around 18% of the votes indicated very high air movement sensation and 30% less air movement preference in buildings operating with air-conditioning. Furthermore, air movement acceptability was approximately 100% and 60% for thermal comfort and thermal discomfort conditions, respectively (Tables S1 and S2, in the Supplementary data).

There was a high concentration of neutral or slightly dry/wet sensation and preference for no change in humidity for users in thermal comfort, as expected. Contrarily, more users in thermal discomfort voted for slightly dry/wet or dry/wet sensation and preference for lower or higher humidity. Even for users in thermal discomfort, there was a very low percentage of votes indicating very dry/wet sensation – less than 5% for all cases. In mixed-mode under natural ventilation mode, the percentage of votes indicating wet sensation and preference for less humidity was higher in comparison to dry sensation and preference for more humidity, while the opposite occurred in buildings operating with air-conditioning. The humidity acceptability was close to 90% and 60% for thermal comfort and thermal discomfort conditions, respectively. It is interesting the significant percentage of responses "I do not know how to answer" for users in thermal comfort (between 5.0% and 13.2%) and especially in thermal discomfort (between 10.9% and 22.5%) (Tables S1 and S2, in the Supplementary data).

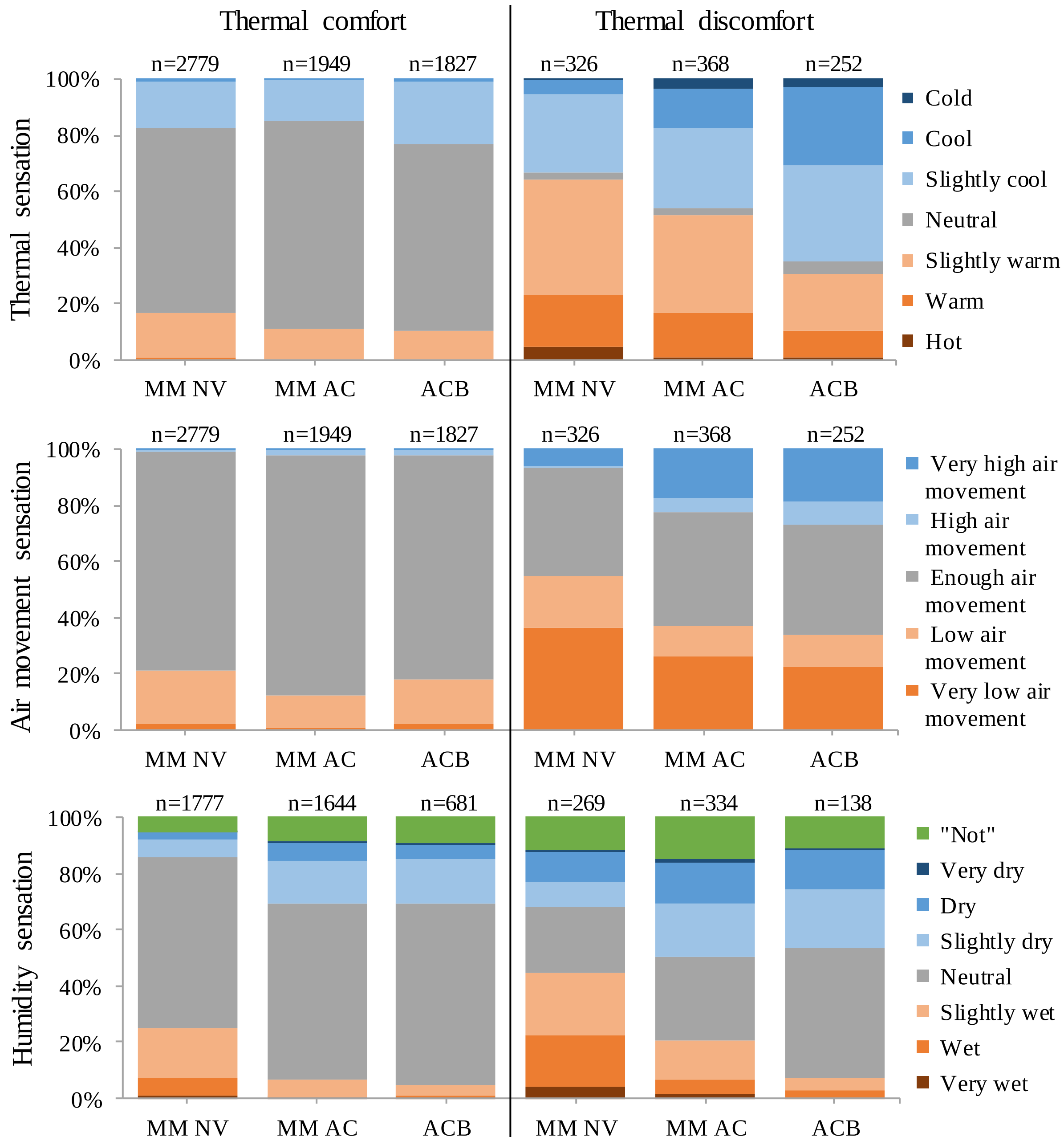


Fig. 11: Frequency of thermal, air movement and humidity sensation votes for each building ventilation type for users in thermal comfort and thermal discomfort

As shown in Fig. 12, in all buildings users in thermal comfort considered the air quality predominantly neutral or satisfactory, with less than 10% of dissatisfaction votes. On the other hand, occupants in thermal discomfort felt predominantly neutral or dissatisfied with the air quality, with around only 20% satisfied users. However, there was a low percentage of very dissatisfied votes – less than 7% for all cases. It is noteworthy that the building with central air-conditioning system presented the highest percentage of air quality satisfaction, for users in thermal comfort and discomfort. Regarding the “Air is stuffy” problem, there was a high concentration of votes around “neutral” for users in thermal comfort and a greater number of votes indicating a big problem for thermal discomfort. For "Air is not clean" and "Air is odorous" problems, votes concentrated mainly between neutral and a big problem, for users in thermal comfort and discomfort. It is notable the significant percentage of votes “It is not a problem” for “Air is stuffy” (around 10%), “Air is not clean” (around 30%) and “Air is odorous” (around 60%), for users in thermal comfort and discomfort (Tables S3 and S4, in the Supplementary data).

Similar analyses evaluated the distribution of thermal, air movement and humidity sensation, preference and acceptability votes according to the season, for users in thermal comfort and discomfort. The results obtained were similar to those observed in the previous analyses. It is noteworthy that in all seasons there was a similar distribution of votes indicating warmer and cooler preference – for example, similar preference for warmer and cooler environment in winter (around 48% for users in thermal discomfort). For thermal discomfort condition, it is interesting the significant percentage of dry sensation (34.2%) and preference for more humidity (28.5%) in summer – which is probably due to the air dryness caused by air-conditioners, used predominantly in summer. On the other hand, in winter there was a significant percentage of votes indicating wet sensation (41.8%) and preference for less humidity (30.5%). In addition, for users in thermal discomfort, the highest percentages of thermal, air movement and humidity acceptability occurred in intermediate seasons.

Therefore, users in thermal comfort tended to be satisfied with the environmental conditions, while those in thermal discomfort tended to prefer some change. Thermal, air movement and humidity acceptability remained above 80% for thermal comfort and above 50% for thermal discomfort conditions. Thus, all subjective variables presented some influence on users’ thermal comfort and air quality perception.

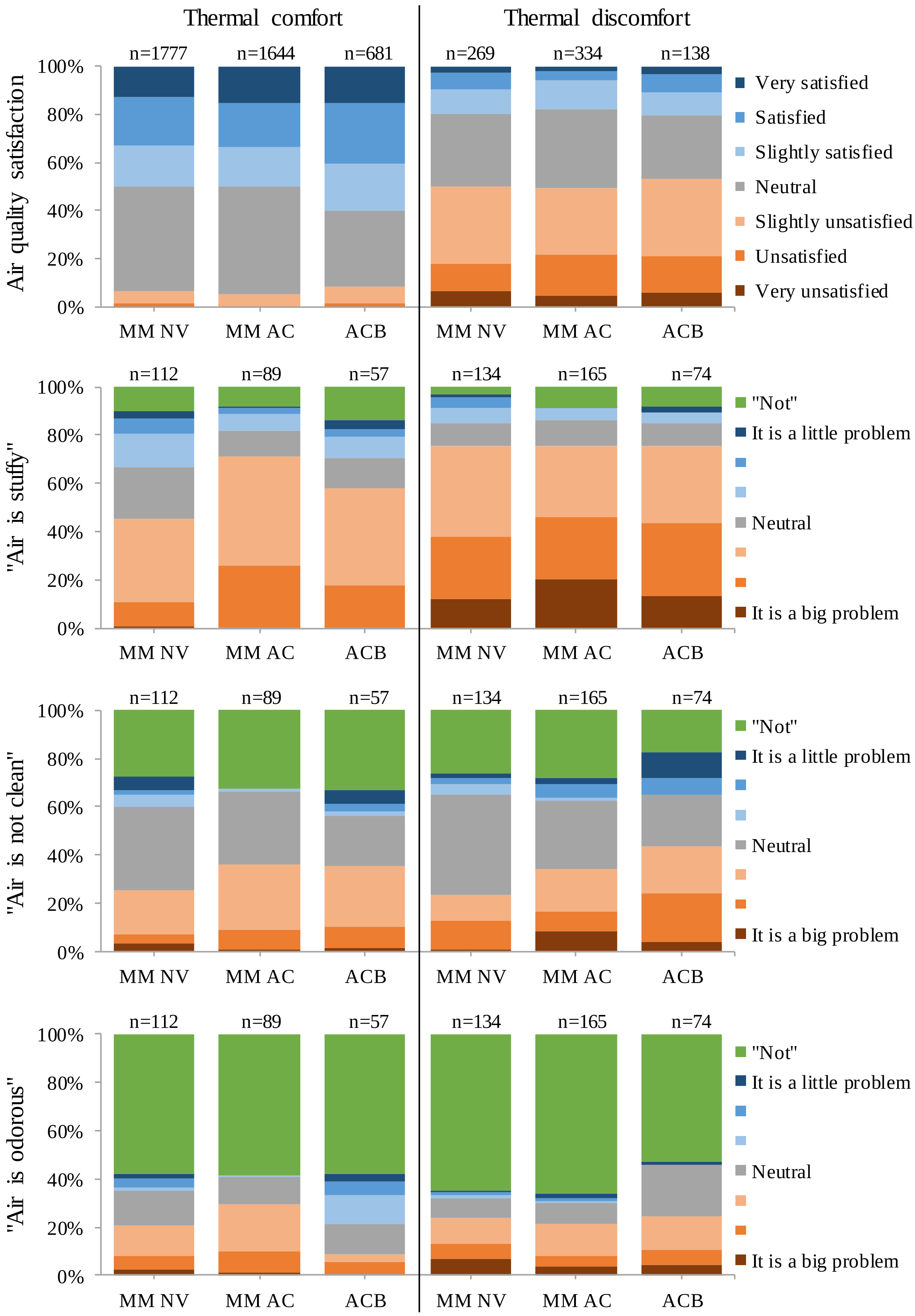


Fig. 12: Frequency of air quality satisfaction and air quality problems votes for each building ventilation type for users in thermal comfort and thermal discomfort

4 Conclusions

In this study, the influence of environmental variables on users' thermal comfort and air quality perception was evaluated based on 7564 data collected in office buildings in Florianópolis, southern Brazil. One building with central air-conditioning system and three mixed-mode buildings, in which there was alternation between natural ventilation mode and air-conditioning mode according to user preference, were analysed. For all buildings, ASHRAE 55 analytical model underestimated occupants' thermal acceptability and comfort. Thus, this work supports the use of the adaptive model of thermal comfort for mixed-mode buildings under natural ventilation operation because it resulted in similarity between the estimated and actual thermal acceptability.

The results showed that an increase in air temperature and humidity ratio tended to increase thermal sensation and preference ($p<0.001$). However, except in mixed-mode buildings operating with air-conditioning, air speed did not influence thermal and air movement sensation and preference ($p>0.05$). Since thermal acceptability was associated with air movement acceptability, there was an indirect effect of air movement on thermal comfort. It is noteworthy that this study was limited to air speed concentration around 0.1 m/s, so the results were representative of conditions with low air movement predominance.

In all buildings, users in thermal comfort tended to be satisfied with the environmental conditions, *i.e.* thermal, air movement and humidity acceptabilities were above 80%. On the other hand, occupants in thermal discomfort tended to prefer some change in air temperature, air speed or humidity. In general, people in mixed-mode buildings in natural ventilation mode were more likely to accept the thermal environment, according to the adaptive thermal comfort theory. In this way, hybrid ventilation strategy is recommended for energy savings as there is a decrease in the use of air-conditioning.

In all seasons, users felt predominantly neutral or satisfied with air quality, even for high air temperature and humidity ratio. Air quality satisfaction was high for thermal, air movement and humidity sensation votes around neutrality; on the other hand, air quality dissatisfaction was predominant when the environment was considered warm, with low air movement and wet. No defined trend was identified between CO_2 concentration and air quality satisfaction, so the latter might be influenced by other factors. In this study, only indoor CO_2 concentration was considered, but future research must consider measuring other parameters (such as outdoor CO_2 concentration, presence of fungi and bacteria, particulate matter, among others) for a complete indoor air quality assessment. Confirming the results of other authors, it was verified the importance of adequate ventilation in internal environments to ensure good air quality and potentially to prevent the spread of airborne diseases.

Therefore, this work contributed to understanding the direct and indirect effects of environmental variables on occupants' thermal comfort and air quality perception in office buildings located in the Brazilian humid subtropical climate. Besides air temperature, air movement, humidity and pollutants concentration, future studies should explore the influence of other factors on thermal comfort and air quality perception, such as skin humidity, personal control of air movement and previous exposure to air-conditioning. Furthermore, other research in humid subtropical climate should be carried out in different building types (such as residential, industrial and historic buildings) and consider visual and acoustic comfort, which can interfere in users' satisfaction and performance.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/

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