Article

Assessment of air quality perception and its effects on users' thermal comfort in office buildings

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Abstract: Since people spend most of their time in indoor environments, the objective of this work was to study indoor air quality and its effects on users' thermal comfort. Based on previous data from a building with a central air-conditioning system and two mixed-mode buildings located in the humid subtropical climate of Florianópolis, southern Brazil, statistical analyses were performed. Each user subjective answer obtained through a questionnaire was combined with the corresponding environmental conditions – measured using microclimate stations, a portable thermo-anemometer and a CO_2 analyser. Results showed that improvement in air quality was associated with the reduction of air temperature and humidity ratio. Also, there was a significant influence of thermal, air movement and humidity sensation and acceptability of air quality perception. Users felt more satisfied or neutral with air quality for being in thermal comfort, and not because of the CO_2 level – which means that air quality perception is influenced by factors other than CO_2. This study recommends the implementation of an air exchange device in split air-conditioners with air recirculation used in mixed-mode buildings in Brazil. It is important to provide suitable indoor ventilation to reduce pollutants concentration, ensure good air quality and prevent respiratory diseases.

Keywords: air quality; carbon dioxide (CO_2); thermal comfort; office buildings; mixed-mode buildings.

1. Introduction

Nowadays, it is estimated that people spend 60% to 90% of their time in indoor environments such as residences, educational institutions and offices [1-3]. In this way, it is important to study indoor air quality and its effects on thermal comfort since they are related to users' satisfaction, performance and health [4-6]. In fact, research has shown that high concentrations of pollutants have direct and indirect adverse health effects since air-conditioned environments can contribute to respiratory and cardiovascular diseases [7,8].

Air quality is associated with physical, chemical and biological characteristics of indoor air, including the concentration of pollutants like carbon dioxide (CO_2). It is known that high CO_2 concentration in indoor environments is an outcome of human metabolism and lack of indoor air exchange – mainly due to the air recirculation by air-conditioners [7,9]. One of the main strategies that contribute to the reduction of pollutants concentration and improvement of air quality is suitable air circulation in order to allow air exchange between indoor and outdoor environments [10-13]. For this purpose, natural ventilation with portable air cleaners and mechanical ventilation systems with particle filters are strategies indicated for removing indoor air pollutants [7,11].

In this context, the relationship between environmental variables, air quality perception and thermal comfort has been researched in distinct places such as climatic chambers [14-16], classrooms [17-19], residences [20] and offices [21,22] – mostly in Eu-

rope, Asia and North America. Thus, it is noteworthy the scarcity of analyses involving air quality in Brazil, so more studies are required in the country.

In general, works in climatic chambers found that high air temperature and humidity tend to worsen the air quality perception due to insufficient respiratory cooling [14,16]. In particular, the air inhaled by users was considered warmer, stuffy and less acceptable as temperature and humidity increased. On the other hand, air movement significantly improved air quality satisfaction and users' thermal comfort; and the use of fans increased air movement and humidity acceptability, without causing discomfort due to dry eyes sensation [14,16]. Also, a study conducted in an educational building with a central air-conditioning system in China found that the indoor environmental quality was considered acceptable under conditions with lower air temperature, relative humidity and CO_2 concentration means [19]**Error! Reference source not found.**.

Research in offices with central air-conditioning systems in the United States evaluated the effect of air movement on air quality satisfaction for men and women, under low air movement environment [21]. Women felt more satisfied with air quality as air speed increased, while the opposite was observed for men. A work in naturally ventilated office buildings in Germany verified a weak correlation between the seasons of the year and the indoor air quality perception [22]. However, the authors noticed that the air quality was slightly influenced by dry air perception in winter, while it was slightly related to indoor air temperature satisfaction in summer.

In naturally ventilated houses in India, a weak correlation between indoor air quality perception and thermal sensation and comfort was identified [20]. It was noted that most of the users considered the air quality neutral, despite high outdoor pollutants concentration – which may be explained by the fact that occupants were accustomed to this condition. In addition, research found that users less satisfied with indoor environmental quality had lower learning performance in classrooms [18,19].

The comparison of studies showed that air quality could be influenced by different factors, such as environmental conditions, pollutants concentration and ventilation type. In this way, it is important to carry out further investigations relating to environmental variables, air quality perception and users' thermal comfort.

The aim of this work is to assess the occupants' perception related to indoor air quality and its effects on thermal comfort based on data from office buildings located in the humid subtropical climate of Florianópolis, southern Brazil. The specific objectives of this study are (1) to evaluate the impact of air temperature, air speed, air humidity and CO_2 concentration on air quality satisfaction, (2) to analyse the influence of air quality perception on occupants' thermal comfort, and (3) to raise awareness of the importance of the suitable indoor ventilation to ensure good air quality.

2. Materials and Methods

2.1. Study contextualisation

In this study, analyses were based on data collected in a building with a central air-conditioning system (ACB) and two mixed-mode buildings (MMB1 and MMB2), in which there was alternation between natural ventilation (NV) and air-conditioning (AC) modes according to the users' preference. All buildings are made of reinforced concrete and have open office environments. Mixed-mode buildings were built in the 1990s, and the building with a central air-conditioning system was built in 1979. The total built area of MMB1 is 6.200 m², MMB2 is 3.090 m² and ACB is 27.432 m². In all buildings, users were free to choose their clothing and there were individual portable fans on some workstations, controlled by the occupants.

The three buildings are located in Florianópolis, southern Brazil. According to the Köppen-Geiger classification [23], the climate is classified as Cfa (humid subtropical climate). The city has hot summers and mild winters, with annual mean outdoor air temperature equal to 20.9 °C, varying from 16.4 °C in July to 25.1 °C in February. Florianópolis is located on an island in the Atlantic Ocean, and the air humidity is high

throughout the year, with annual mean outdoor relative humidity equal to 80.4%. Figure 1 shows the mean outdoor air temperature and outdoor relative humidity.
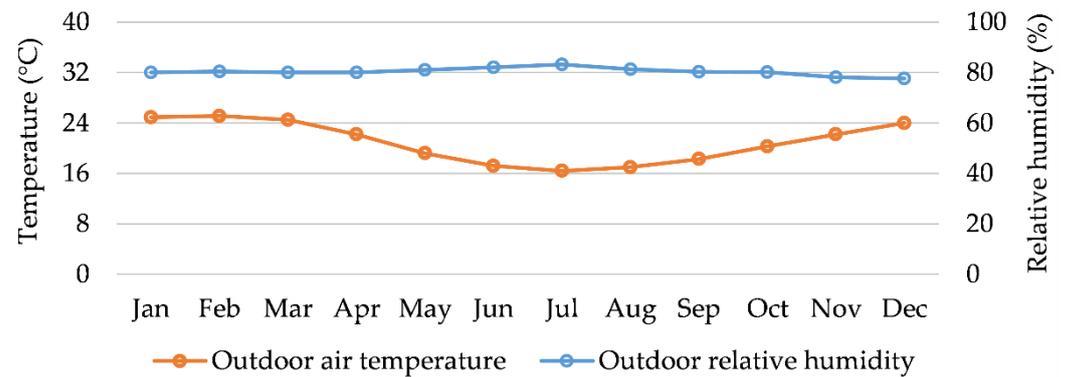

Figure 1. Mean outdoor air temperature and outdoor relative humidity. Source: Climatological Standards (1981-2010) [24].

For measurements of indoor environmental variables, microclimate stations were used to measure air temperature, globe temperature, air speed and relative humidity (recorded at five-minute intervals) at 0.60 m from the floor level and near the geometric centre of the rooms, following ASHRAE 55 recommendations [25]. A portable thermo-anemometer was also used for spot measurements of air temperature and air speed near the air vents of the air-conditioning system, the windows and the portable fans. A CO_2 analyser measured the concentration of indoor carbon dioxide at 1.5 m from the floor level. The sensor was placed between 1.5 m and 2.0 m from people and walls, according to ISO 16000-1:2004 [26] and ISO 16000-26:2012 [27].

At the same time, subjective data were obtained from electronic questionnaires with general questions about users' characteristics and questions about thermal, air movement, air humidity and air quality perception. The questionnaires were applied to occupants every twenty minutes for five times during a work shift. Clothing insulation and metabolic activity were estimated according to ASHRAE 55 [25]. Data were collected *in situ* from April 2015 to March 2016 and covered all seasons, including different environmental characteristics that better represent the climatic reality during the year. Further information on field data collection can be found in [28].

2.2. Statistical analyses

Originally, each subjective answer of a participant at a given time was combined with the environmental conditions measured at the time of the response. Based on this, the relationship between environmental and subjective variables was assessed through statistical analyses, such as linear regressions, correlations and bar charts. In this work, absolute humidity was considered in all analyses involving humidity, instead of relative humidity [29-31]. ISO 7726:1998 [32] states that absolute humidity can be obtained from air temperature and relative humidity measurements, and one way of expressing it is the humidity ratio.

Table 1 shows the parameters and corresponding scales for the questions and answers in the questionnaire. The scales were based on the work [33] and tested in a pilot study. It is noteworthy that air quality perception refers to users' satisfaction with air quality in their workplaces. Thus, occupants unsatisfied with air quality assessed the problems "Air is stuffy", "Air is not clean" and "Air is odorous", which have a seven-point scale: -3 ("It is a big problem") to +3 ("It is a small problem"), and the extra option "Not" ("It is not a problem").

Table 1. Parameters and respective 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 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 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 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

3.1. Data overview

In order to evaluate the air quality perception and CO_2 concentration in indoor environments of office buildings in Florianópolis, 870 environmental and subjective data were analysed.

In this study, the following environmental variables were considered: air temperature (T_a), mean daily outdoor air temperature (T_{out}), air speed (V_a), relative humidity (RH), mean daily outdoor relative humidity (RH_{out}), humidity ratio (W_a) and carbon dioxide concentration (CO_2) (Table 2). In all buildings, the mean air temperature and air speed were close to 24°C and 0.1 m/s, respectively. Also, the mean outdoor air temperature and outdoor relative humidity were, respectively, lower and higher in mixed-mode buildings under natural ventilation operation. This indicates that natural ventilation was mainly used during the intermediate seasons, i.e. autumn and spring, and winter. Higher relative humidity and humidity ratio were observed in natural ventilation mode in comparison to air-conditioning mode, because of the air humidity reduction due to the use of air-conditioning [34]. Regarding the CO_2 concentration, higher means and standard deviations were obtained in mixed-mode buildings operating with air-conditioning

in comparison to natural ventilation mode and the building with a central air-conditioning system. This result is due to indoor air exchange absence, mainly due to the air recirculation caused by split air-conditioners in mixed-mode buildings.

In all buildings, similar means were verified between users' age, weight, height, BMI (Body Mass Index) and metabolic activity (Table 2). Otherwise, clothing insulation was higher in natural ventilation mode in comparison to air-conditioning mode. This result validates the preponderance of natural ventilation use in intermediate seasons and winter since buildings had no heating system.

Table 2. Environmental and occupant-related variables according to building and operation mode.

	Variables	MMB1		MMB2		ACB
	(mean ± S.D.)	NV (n=80)	AC (n=55)	NV (n=232)	AC (n=329)	AC (n=174)
Environmental	Ta (°C)	23.4 ± 1.5	23.8 ± 0.9	24.4 ± 1.2	24.6 ± 0.9	24.4 ± 0.5
	Tout (°C)	18.7 ± 2.1	24.5 ± 2.4	20.2 ± 2.8	25.2 ± 2.4	23.2 ± 0.5
	Va (m/s)	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.1 ± 0.0	0.1 ± 0.2
	RH (%)	67 ± 3	60 ± 2	69 ± 7	57 ± 4	61 ± 3
	RHout (%)	81 ± 9	76 ± 0	85 ± 4	77 ± 3	71 ± 7
	Wa (g/kg)	10.01 ± 0.34	9.12 ± 0.36	10.96 ± 1.52	9.15 ± 0.84	9.66 ± 0.51
	CO_2 (ppm)	661 ± 90	1046 ± 143	449 ± 67	774 ± 207	581 ± 40
Occupant-related	Age (years)	41 ± 8	46 ± 10	37 ± 12	36 ± 11	40 ± 9
	Weight (kg)	64 ± 8	72 ± 13	71 ± 15	70 ± 14	81 ± 16
	Height (m)	1.65 ± 0.05	1.69 ± 0.08	1.68 ± 0.10	1.67 ± 0.09	1.75 ± 0.07
	BMI (kg/m²)	23.5 ± 2.6	24.9 ± 3.1	25.0 ± 4.2	24.7 ± 3.9	26.4 ± 4.0
	Clothing insulation	0.88 ± 0.31	0.54 ± 0.06	0.69 ± 0.15	0.60 ± 0.11	0.62 ± 0.09
	Metabolic activity	1.2 ± 0.2	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1

3.2. Air quality satisfaction

Figures 2 and 3 show the distribution of air quality satisfaction votes according to environmental and subjective variables related to air temperature and humidity, considering data from all buildings. The air temperature and humidity ratio intervals with less than ten observations were not considered in the corresponding analyses. In general, there was a slight tendency to increase air quality dissatisfaction and reduce air quality neutrality as increased air temperature and humidity ratio – except for 11 g/kg and 12 g/kg, which had a low percentage of dissatisfaction votes. Similar results were obtained by [14-16]. The highest percentages of users satisfied with air quality occurred for air temperature equal to 24°C (48.1% satisfied) and humidity ratio equal to 12 g/kg (67.7% satisfied) (Figure 2). It is noteworthy that regressions between the environmental variables and air quality satisfaction were significant for air temperature ($p<0.05$) and non-significant for humidity ratio ($p>0.05$).
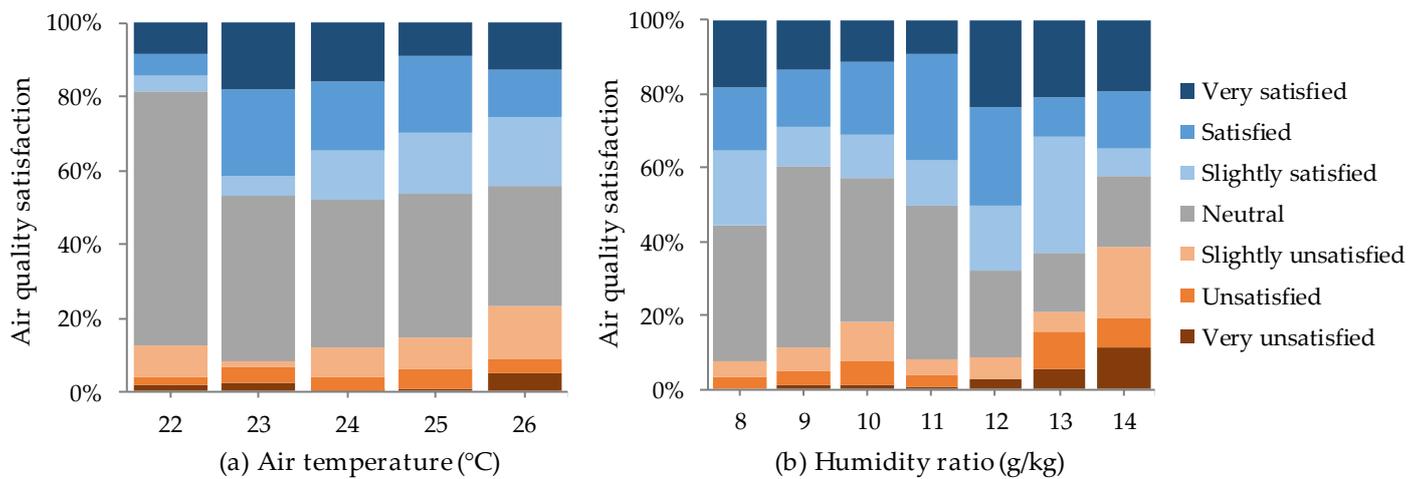
Figure 2. Distribution of air quality satisfaction votes according to environmental variables.
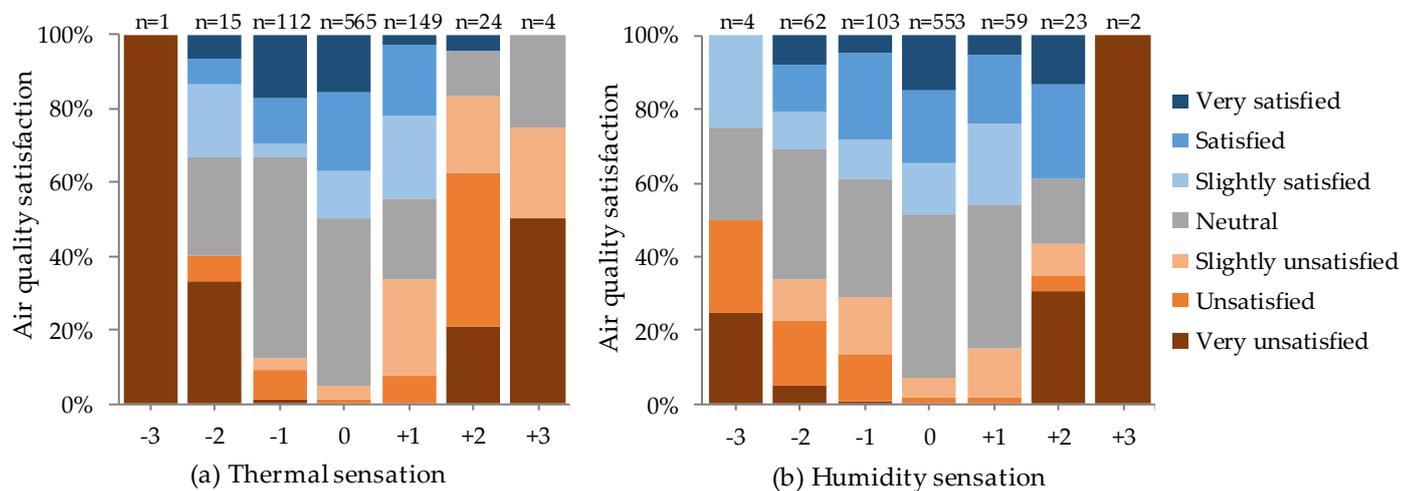

Figure 3. Distribution of air quality satisfaction votes according to subjective votes.

Regarding the subjective variables, the votes related to the response "I do not know how to answer" were not included in the analysis of humidity sensation. For subjective votes close to neutral (between -1 and +1), air quality was considered predominantly neutral or satisfactory. On the other hand, extreme subjective votes were associated with high air quality dissatisfaction – above 40% in most cases (Figure 3). Regressions between thermal, air movement and humidity sensation and the air quality satisfaction were significant ($p < 0.05$), so there was a significant influence of subjective variables on air quality perception.

Similar analyses assessed the distribution of air quality satisfaction votes according to thermal, air movement and humidity acceptability. The acceptability condition was related to the predominance of neutrality or satisfaction with air quality (above 90%), while unacceptability was associated with greater air quality dissatisfaction (above 60%).

Table 3 shows the distribution of air quality satisfaction votes according to building ventilation type, for users in thermal comfort and discomfort. For thermal comfort condition, most of the users considered the air quality neutral or satisfactory, with less than 10% of dissatisfaction votes. Contrarily, occupants in thermal discomfort evaluated the air quality neutral or unsatisfactory, with a low percentage of satisfied users. It is noteworthy that the fully air-conditioned building had the highest percentage of air quality satisfaction, for users in thermal comfort and discomfort. Thus, there was a significant influence of air quality perception on users' thermal comfort.

A similar analysis evaluated the distribution of air quality satisfaction according to the season. It was found that in all seasons, less than 20% of the users considered air quality unsatisfactory. The highest percentages of users satisfied with air quality occurred in summer (70.4%) and autumn (72.0%).

Table 3. Distribution of air quality satisfaction votes according to building ventilation type, for users in thermal comfort and discomfort.

Air quality satisfaction	Thermal comfort (%)			Thermal discomfort (%)		
	MM NV n=263	MM AC n=339	ACB n=143	MM NV n=49	MM AC n=45	ACB n=31
+3 Very satisfied	11.8	15.9	19.6	0.0	2.2	0.0
+2 Satisfied	21.3	15.0	34.3	2.0	4.4	19.4
+1 Slightly satisfied	14.8	10.6	17.5	0.0	15.6	16.1
0 Neutral	45.2	52.2	19.6	30.6	24.4	25.8
-1 Slightly unsatisfied	4.9	5.9	4.9	30.6	17.8	19.4
-2 Unsatisfied	1.9	0.3	4.2	18.4	31.1	9.7
-3 Very unsatisfied	0.0	0.0	0.0	18.4	4.4	9.7

Figure 4 shows the frequency of votes of the air quality problems "Air is stuffy", "Air is not clean" and "Air is odorous", assessed by occupants unsatisfied with air quality. The frequency of votes indicating a big problem was much higher than those considering a little problem for the "Air is stuffy" problem. Also, dirty air perception was classified as neutral by the majority of votes in this category. Different than expected, the existence of odour was not classified as a problem by 74.1% of the occupants. The causes of "Air is odorous" problem were investigated, and users were able to choose more than one option per answer (Figure 5). The main reasons that contributed to the problem were the smell of outdoor pollution, food and cigarettes. Otherwise, the factors that contributed less were the smell of other people and perfume.
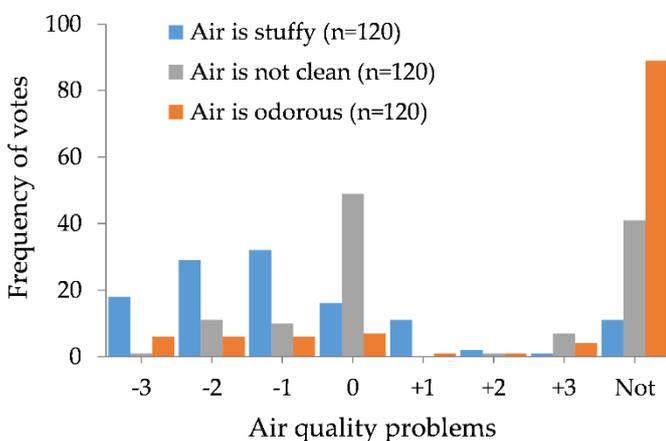

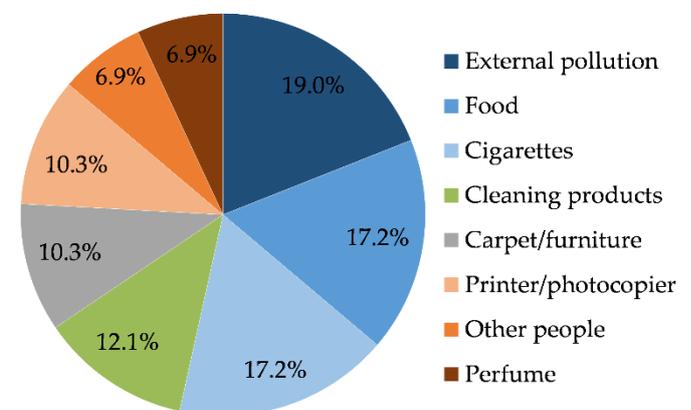**Figure 4.** Frequency of air quality problems votes.

Figure 5. Causes of "Air is odorous" problem.

3.3. CO_2 concentration

Figure 6 shows the frequency of CO_2 concentration indoors, measured in parts per million (ppm), according to building ventilation type. In mixed-mode buildings, the CO_2 level varied between 300 and 900 ppm in natural ventilation mode and 400 and 1300 ppm in air-conditioning mode, while in the building with a central air-conditioning system CO_2 remained between 500 and 600 ppm. Thus, the CO_2 concentration range was wider and higher in mixed-mode buildings in comparison to the fully air-conditioned building – as obtained by [17]. It is noteworthy that the CO_2 level in mixed-mode buildings under natural ventilation operation was predominantly lower compared to other building ventilation types.
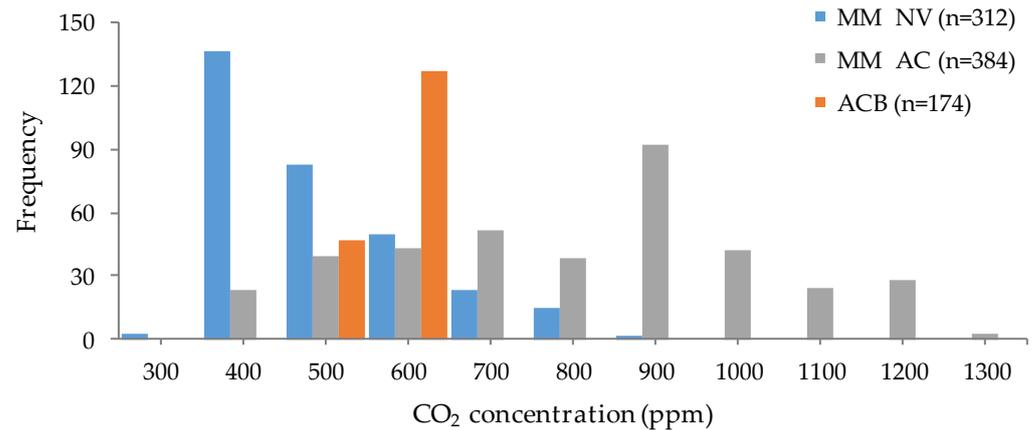
Figure 6. Frequency of CO_2 concentration according to building ventilation type.

In general, the required ventilation rate and CO_2 concentration are specified as adequate indoor air quality criteria, although there is no common index according to national and international standards [5]. In Brazil, ANVISA Resolution 09/2003 [35] specifies 1000 ppm, *i.e.* 0.1% of the air composition, as the maximum recommended CO_2 concentration in shared air-conditioned environments. In this study, mixed-mode buildings in air-conditioning mode had high levels of indoor pollutants, exceeding the recommended limit of 1000 ppm. On the other hand, although the high energy consumption due to the continuous air-conditioning operation (the windows were sealed), the building with a central air-conditioning system had an air exchange system, which guaranteed CO_2 concentration below the recommended limit. Therefore, the implementation of an air exchange device in split air-conditioners used in Brazilian mixed-mode buildings is highly recommended.

Comparing CO_2 concentrations for each season, higher mean and standard deviation were obtained in summer (774 ± 214) compared to winter (516 ± 77), with moderate levels in intermediate seasons (582 ± 195). Thus, the lowest CO_2 means occurred in seasons with a predominant use of natural ventilation in mixed-mode buildings, confirming the importance of ventilation to reduce indoor air pollutants. Similarly, studies carried out on residential buildings located in a temperate climate in northern China [11] and Mediterranean and continental climates in Spain [36] also found lower CO_2 concentrations when the buildings operated with natural ventilation.

Correlations between air temperature, air speed and humidity ratio and the CO_2 concentration were performed for each building ventilation type (Figure 7). Higher air temperature and humidity ratio were related to lower CO_2 levels in mixed-mode buildings in both operation modes. Also, higher air speed was related to lower CO_2 concentration in mixed-mode buildings under natural ventilation – as expected, because air movement increases pollutants dispersion, reducing CO_2 level indoors [37]. Contrarily, in air-conditioning mode, the CO_2 concentration was higher as air speed was greater since there was air recirculation indoors. It can be seen some high CO_2 levels in mixed-mode buildings operating with natural ventilation, which occurred when the windows were closed (winter). In this case, there was no adequate ventilation of the indoor environments, causing a higher CO_2 concentration. Thus, it is important to promote the use of air exchange through mechanical ventilation during these months.

In the building with a central air-conditioning system, air temperature and air speed were not correlated with the CO_2 concentration, while higher humidity ratio was related to lower CO_2 levels (Figure 7). It is noteworthy that regressions between the environmental variables and CO_2 concentration were significant ($p < 0.05$), except for air temperature and air speed in the fully air-conditioned building ($p > 0.05$).
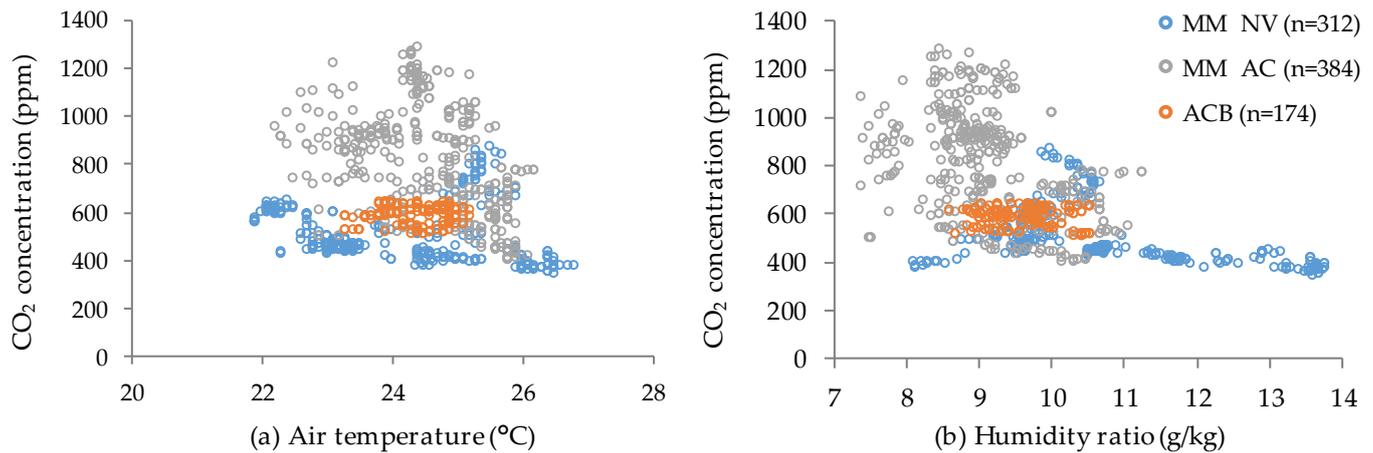
Figure 7. Correlations between environmental variables and CO_2 concentration.

Similar analyses involved correlations between CO_2 concentration and thermal, air movement and humidity sensation, for each building ventilation type. Except for a very weak correlation between CO_2 and air movement and humidity sensation in mixed-mode buildings operating with air-conditioning ($p<0.05$ and $R^2=0.01$), all other correlations were non-significant ($p>0.05$).

Figure **8** shows the distribution of air quality satisfaction votes, thermal comfort and mean air temperature and humidity ratio according to CO_2 concentration (intervals with less than ten observations were not taken into account). There was little variation in air quality perception as CO_2 concentration increased, with no clear trend between these variables. 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 an increase in thermal comfort, indicating that higher CO_2 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 the mean CO_2 was higher for users satisfied or neutral with air quality (667 ± 224 ppm) compared to dissatisfied occupants (583 ± 155 ppm). This result is due to the fact 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.

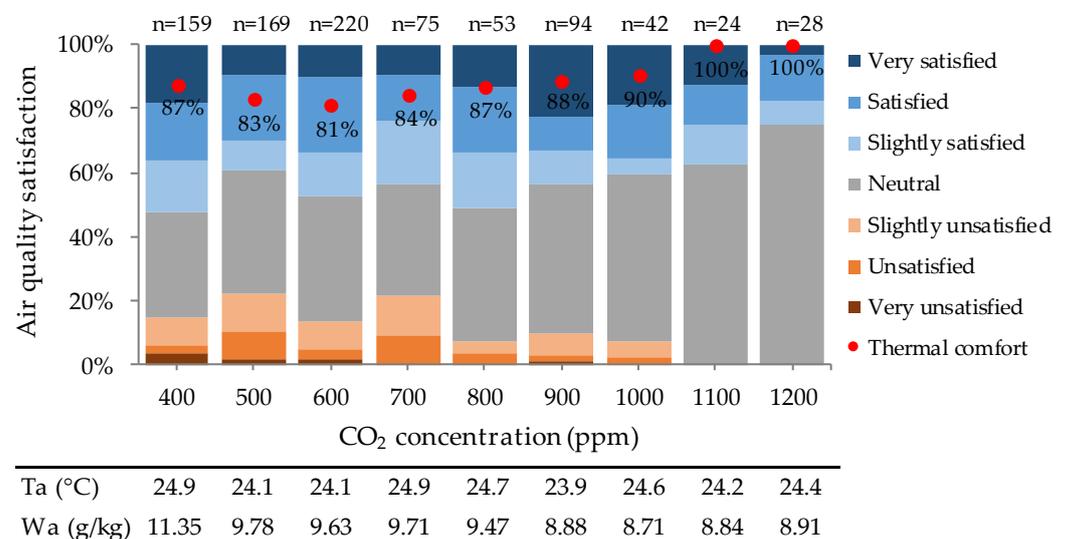|									
Ta (°C)	24.9	24.1	24.1	24.9	24.7	23.9	24.6	24.2	24.4
Wa (g/kg)	11.35	9.78	9.63	9.71	9.47	8.88	8.71	8.84	8.91

Figure 8. Distribution of air quality satisfaction votes, thermal comfort and mean air temperature and humidity ratio according to CO_2 concentration.

4. Conclusions

This work assessed the air quality perception and its effects on users' thermal comfort in office buildings located in the humid subtropical climate of Florianópolis, southern Brazil. A total of 870 data from a building with a central air-conditioning system and two mixed-mode buildings, which alternated between natural ventilation and air-conditioning modes, were considered. In general, an increase in air temperature and humidity ratio tended to slightly increase dissatisfaction with air quality. The highest percentages of users satisfied with air quality occurred for air temperature equal to 24°C (48.1% satisfied) and humidity ratio equal to 12 g/kg (67.7% satisfied). It is noteworthy that this study was limited to air speed concentration around 0.1 m/s, which made it difficult to carry out some analyses involving air movement.

There was a significant influence of thermal, air movement and humidity sensation on air quality perception since air quality was considered predominantly neutral or satisfactory for subjective votes close to neutral and unsatisfactory for extreme subjective votes. Similarly, the acceptability of environmental variables was related to the predominance of neutrality or satisfaction with air quality (above 90%), while unacceptability was associated with greater air quality dissatisfaction (above 60%). In all buildings, users in thermal comfort evaluated air quality as neutral or satisfactory (more than 90% of votes), and those in thermal discomfort considered the air quality mainly neutral or unsatisfactory. Thus, there was a significant influence of air quality perception on users' thermal comfort. Air quality problems "Air is stuffy", "Air is not clean" and "Air is odorous", assessed by occupants unsatisfied with air quality, were considered mostly a big problem than a little problem. Also, the main reasons that contributed to "Air is odorous" problem were the smell of outdoor pollution, food and cigarettes.

Mixed-mode buildings operating with split air-conditioning with air recirculation had high levels of indoor pollutants, with some concentrations exceeding the ANVISA Resolution 09/2003 recommended limit of 1000 ppm in Brazil. Contrarily, the building with a central air-conditioning system had an air exchange system, which guaranteed CO_2 concentrations below the recommended limit. The lowest CO_2 levels in mixed-mode buildings occurred in seasons with a predominant use of natural ventilation, except in winter when the windows were closed. So, this study recommends mechanical ventilation during winter and the implementation of air exchange devices to be used when split air-conditioners are in operation in mixed-mode buildings. Suitable ventilation of indoor environments is important to reduce pollutants concentration, ensure good air quality and prevent respiratory diseases. Therefore, this work warns about the urgent need for improving air exchange in Brazilian buildings.

In general, there was no clear trend between CO_2 concentration and air quality satisfaction. Also, an increase in CO_2 level was related to a reduction in humidity ratio and an increase in thermal comfort. Thus, users felt more satisfied or neutral with air quality for being in thermal comfort, and not because of CO_2 level – which means that air quality perception is influenced by factors other than CO_2. It is noteworthy that this work evaluated air quality only through users' perception based on votes from an electronic questionnaire and measurements of indoor CO_2 concentration. So it is important that further studies also consider the measurement of parameters related to air quality – such as indoor and outdoor CO_2 concentration, presence of fungi and bacteria, particulate matter, radon and ozone concentration, and volatile organic compounds – in order to obtain a complete assessment of indoor air quality. Furthermore, future research should be carried out in different building types in humid subtropical climates and assess users' air quality perception separately for different occupants.

References

1. Brasche, S.; Bischof, W. Daily time spent indoors in German homes – Baseline data for the assessment of indoor exposure of German occupants. *Int. J. Hyg. Envir. Heal.* **2005**, 208(4), 247-253, https://doi.org/10.1016/j.ijheh.2005.03.003.
2. European Commission. Indoor air pollution: new EU research reveals higher risks than previously thought, 2003. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_03_1278 (accessed on 27 January 2020).
3. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P.; Behar, J.V.; Hern, S.C.; Engelmann, W.H. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J. Expo. Anal. Env. Epid.* **2001**, 11, 231-252, https://doi.org/10.1038/sj.jea.7500165.
4. Che, W.W.; Tso, C.Y.; Sun, L.; Ip, D.Y.K.; Lee, H.; Chao, C.Y.H.; Lau, A.K.H. Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system. *Energ. Buildings* **2019**, 201, 202-215, https://doi.org/10.1016/j.enbuild.2019.06.029.
5. Khovalyg, D.; Kazanci, O.B.; Halvorsen, H.; Gundlach, I.; Bahnfleth, W.P.; Toftum, J.; Olesen, B.W. Critical review of standards for indoor thermal environment and air quality. *Energ. Buildings* **2020**, 213, 109819, https://doi.org/10.1016/j.enbuild.2020.109819.
6. Kim, J.; Hong, T.; Kong, M.; Jeong, K. Building occupants' psycho-physiological response to indoor climate and CO_2 concentration changes in office buildings. *Build. Environ.* **2020**, 169, 106596, https://doi.org/10.1016/j.buildenv.2019.106596.
7. Campos, E.C.; Guedes, B.A.M. Relatório técnico: Impactos da pandemia de COVID-19 sobre sistemas de ar condicionado e climatização [Technical report: Impacts of COVID-19 pandemic on air-conditioning systems and climatization], 2020. Available online: https://www2.ufjf.br/noticias/wp-content/uploads/sites/2/2020/07/relatorio_tecnico__impactos_da_pandemia_de_covid_19__sobre_sistemas_de_ar_condicionado_e_climatizacao.pdf (accessed on 15 July 2020).
8. Hoek, G.; Krishnan, R.M.; Beelen, R.; Peters, A.; Ostro, B.; Brunekreef, B.; Kaufman, J.D. Long-term air pollution exposure and cardio-respiratory mortality: a review. *Environ. Health* **2013**, 12, 43, https://doi.org/10.1186/1476-069X-12-43.
9. Hussin, M.; Ismail, M.R.; Ahmad, M.S. Air-conditioned university laboratories: Comparing CO_2 measurement for centralized and split-unit systems. *Journal of King Saud University – Engineering Sciences* **2017**, 29(2), 191-201, https://doi.org/10.1016/j.jksues.2014.08.005.
10. Hamid, A.A.; Johansson, D.; Bagge, H. Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ. *Energ. Buildings* **2020**, 211, 109822, https://doi.org/10.1016/j.enbuild.2020.109822.
11. Liu, J.; Dai, X.; Li, X.; Jia, S.; Pei, J.; Sun, Y.; Lai, D.; Shen, X.; Sun, H.; Yin, H.; Huang, K.; Tan, H.; Gao, Y.; Jian, Y. Indoor air quality and occupants' ventilation habits in China: Seasonal measurement and long-term monitoring. Build. Environ. 2018, 142, 119-129, https://doi.org/10.1016/j.buildenv.2018.06.002.
12. Park, D.Y.; Chang, S. Effects of combined central air conditioning diffusers and window-integrated ventilation system on indoor air quality and thermal comfort in an office. *Sustain. Cities Soc.* **2020**, 61, 102292, https://doi.org/10.1016/j.scs.2020.102292.
13. Sun, Y.; Hou, J.; Cheng, R.; Sheng, Y.; Zhang, X.; Sundell, J. Indoor air quality, ventilation and their associations with sick building syndrome in Chinese homes. *Energ. Buildings* **2019**, 197, 112-119, https://doi.org/10.1016/j.enbuild.2019.05.046.
14. Toftum, J.; Jorgensen, A.S.; Fanger, P.O. Upper limits of air humidity for preventing warm respiratory discomfort. *Energ. Buildings* **1998**, 28(1), 15-23, https://doi.org/10.1016/S0378-7788(97)00018-2.
15. Zhai, Y.; Arens, E.; Elsworth, K.; Zhang, H. Selecting air speeds for cooling at sedentary and non-sedentary office activity levels. *Build. Environ.* **2017**, 122, 247-257, https://doi.org/10.1016/j.buildenv.2017.06.027.
16. Zhai, Y.; Zhang, H.; Zhang, Y.; Pasut, W.; Arens, E.; Meng, Q. Comfort under personally controlled air movement in warm and humid environments. *Build. Environ.* **2013**, 65, 109-117, https://doi.org/10.1016/j.buildenv.2013.03.022.
17. Asif, A.; Zeeshan, M.; Zahanzaib, M. Indoor temperature, relative humidity and CO_2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems. *Build. Environ.* **2018**, 133, 83-90, https://doi.org/10.1016/j.buildenv.2018.01.042.
18. Jamaludin, N.M.; Mahyuddin, N.; Akashah, F.W. Assessment on Indoor Environmental Quality (IEQ) with the application of potted plants in the classroom: case of University Malaya. *Journal of Design and Built Environment* **2017**, 17(2), 1-15, https://doi.org/10.22452/jdbe.vol17no2.1.
19. Lee, M.C.; Mui, K.W.; Wong, L.T.; Chan, W.Y.; Lee, E.W.M.; Cheung, C.T. Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. *Build. Environ.* **2012**, 49, 238-244, https://doi.org/10.1016/j.buildenv.2011.10.001.
20. Indraganti, M.; Rao, K.D. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. *Energ. Buildings* **2010**, 42(3), 273-281, https://doi.org/10.1016/j.enbuild.2009.09.003.

21. Choi, J.; Moon, J. Impacts of human and spatial factors on user satisfaction in office environments. *Build. Environ.* **2017**, 114, 23-35, https://doi.org/10.1016/j.buildenv.2016.12.003.

22. Wagner, A.; Gossauer, E.; Moosmann, C.; Gropp, T.; Leonhart, R. Thermal comfort and workplace occupant satisfaction – Results of field studies in German low energy office buildings. *Energ. Buildings* **2007**, 39(7), 758-769, https://doi.org/10.1016/j.enbuild.2007.02.013.

23. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorol. Z.* **2013**, 22(6), 711–728, https://doi.org/10.1127/0941-2948/2013/0507.

24. Brazil. Ministry of Agriculture, Livestock, and Supply, Brazilian Institute of Meteorology (INE). Climatological standards (1981-2010). Brasília, Brazil, 2018.

25. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ANSI/ASHRAE Standard 55 – 2013: Thermal Environmental Conditions for Human Occupancy. Atlanta, United States of America, 2013.

26. International Organization for Standardization. ISO 16000:1: Indoor air – General aspects of sampling strategy. Geneva, Switzerland, 2004.

27. International Organization for Standardization. ISO 16000:26: Indoor air – Sampling strategy for carbon dioxide (CO_2). Geneva, Switzerland, 2012.

28. Rupp, R.F.; Kim, J.; Dear, R.; Ghisi, E. Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings. *Build. Environ.* **2018**, 135, 1-9, https://doi.org/10.1016/j.buildenv.2018.02.049.

29. Givoni, B.; Khedari, J.; Wong, N.H.; Feriadi, H.; Noguchi, M. Thermal sensation responses in hot, humid climates: effects of humidity. *Build. Res. Inf.* **2006**, 34(5), 496-506, https://doi.org/10.1080/09613210600861269.

30. Nicol, F.; Humphreys, M.; Roaf, S. Adaptive Thermal Comfort Principles and Practice. London, England, 2012.

31. Oliveira, C.C.; Rupp, R.F.; Ghisi, E. Influência da umidade do ar no conforto térmico de usuários de edificações de escritórios localizadas no clima subtropical úmido de Florianópolis/SC [Influence of air humidity on users' thermal comfort in office buildings located in the humid subtropical climate of Florianópolis/SC]. Proceedings of the Encontro Nacional de Conforto no Ambiente Construído. João Pessoa, Brazil, 2019.

32. International Organization for Standardization. ISO 7726: Ergonomics of the thermal environment – Instruments for measuring physical quantities. Geneva, Switzerland, 1998.

33. Ackerly, K.; Brager, G.; Arens, E. Data collection methods for assessing adaptive comfort in mixed-mode buildings and personal comfort systems. UC Berkeley – Indoor Environmental Quality (IEQ), 2012. Available online: https://escholarship.org/uc/item/64p9111k (accessed on 20 January 2021).

34. Damiati, S.A.; Zaki, S.A.; Rijal, H.B.; Wonorahardjo, S. Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season. *Build. Environ.* **2016**, 109, 208-223, https://doi.org/10.1016/j.buildenv.2016.09.024.

35. Brazil. Brazilian Health Regulatory Agency (Anvisa), Resolution nº 9, 2003. Available online: http://portal.anvisa.gov.br/documents/10181/2718376/RE_09_2003_.pdf/8ccafc91-1437-4695-8e3a-2a97deca4e10 (accessed on 20 June 2020).

36. Fernández-Agüera, J.; Domínguez-Amarillo, S.; Alonso, C.; Martín-Consuegra, F. Thermal comfort and indoor air quality in low-income housing in Spain: The influence of airtightness and occupant behaviour. *Energ. Buildings* **2019**, 199, 102-114, https://doi.org/10.1016/j.enbuild.2019.06.052.

37. Suzuki, E.H. Avaliação do conforto térmico e do nível de CO_2 em edifícios de escritório com climatização artificial na cidade de São Paulo [Evaluation of thermal comfort and CO_2 level in office buildings with artificial air-conditioning in the city of São Paulo]. Masters dissertation, Polytechnic School of the University of São Paulo, São Paulo, Brazil, 2010.