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Thermal perception and adaptation in naturally ventilated hospital environments

Karime Zeferino de Souza Alves da Costa [1]
Universidade de São Paulo, São Carlos, SP, Brazil

Eduvaldo Paulo Sichieri [2]
Universidade de São Paulo, São Carlos, SP, Brazil

Abstract

Adaptive comfort is crucial in environmental design, acknowledging people's ability to adjust to thermal conditions actively. It goes beyond static metrics, guiding dynamic and more effective design practices to create environments that promote satisfaction and well-being. This study investigated thermal comfort in naturally ventilated hospital environments at the University Hospital of the Federal University of São Carlos. Thermal conditions were evaluated based on the adaptive model of ASHRAE 55 and occupants' adaptive responses during summer, considering environmental measurements and questionnaires. The results revealed that temperatures in the SADT management and main reception often exceeded the limits of the adaptive model, with average excesses of 2.6°C and 3.01°C, respectively, exacerbating thermal discomfort. Furthermore, passive thermal conditioning strategies, such as tilting ceilings and blinds, were underutilized and questioned for effectiveness by occupants. In response to thermal discomfort, occupants adopted adaptive measures, such as changing positions and consuming cold beverages. Frequent exposure to artificially controlled thermal environments may reduce people's flexibility to adapt to different temperature conditions. Applying the adaptive model of ASHRAE 55 revealed limitations in assessing thermal comfort in hospital environments, highlighting the need to consider occupants' real perceptions and needs. The results emphasize the importance of a holistic and participatory approach to improving thermal comfort in hospital environments, integrating objective parameters and occupants' experiences.

Keywords: thermal comfort, adaptive model, adaptive opportunities, hospital architecture.

Percepção térmica e adaptação em ambientes hospitalares naturalmente ventilados

Resumo

O conforto adaptativo é crucial no design ambiental, reconhecendo a capacidade das pessoas de se ajustarem ativamente às condições térmicas. Vai além das métricas estáticas, orientando práticas de design dinâmicas e mais eficazes para criar ambientes que promovam satisfação e bem-estar. Este estudo investigou o conforto térmico em ambientes hospitalares naturalmente ventilados do Hospital Universitário da Universidade Federal de São Carlos. Utilizando medições ambientais e questionários, foram avaliadas as condições térmicas com base no modelo adaptativo da ASHRAE 55 e as respostas adaptativas dos ocupantes durante o verão. Os resultados revelaram que as temperaturas na chefia SADT e na recepção principal frequentemente excediam os limites do modelo adaptativo, com médias de excesso de 2,6°C e 3,01°C, respectivamente, intensificando o desconforto térmico. Além disso, as estratégias passivas de condicionamento térmico, como forros basculantes e venezianas, foram pouco utilizadas e questionadas quanto à eficácia pelos ocupantes. Em resposta ao desconforto térmico, os ocupantes adotaram medidas adaptativas, como mudanças de posição e consumo de bebidas frias. A exposição frequente a ambientes com controle térmico artificial pode reduzir a flexibilidade das pessoas em se adaptarem a diferentes condições de temperatura. A aplicação do modelo adaptativo da norma ASHRAE 55 revelou limitações na avaliação do conforto térmico em ambientes hospitalares, destacando a necessidade de considerar as percepções e necessidades reais dos ocupantes. Os resultados enfatizam a importância de uma abordagem holística e participativa na melhoria do conforto térmico em ambientes hospitalares, integrando parâmetros objetivos e experiências dos ocupantes.

Palavras-chave: conforto térmico, modelo adaptativo, oportunidades adaptativas, arquitetura hospitalar.

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1. Introduction

Over the past few decades, the study of thermal comfort has evolved into a complex journey. It goes beyond the simple understanding of environmental conditions and delves into the intricate world of human interactions with the built environment. This relentless pursuit of understanding has led to two fundamental approaches: the analytical/static and the adaptive (Lamberts; Dutra; Pereira, 2014).

In the analytical approach, pioneering studies by Fanger laid the foundation for a deeper understanding, using climate-controlled chambers to isolate environmental and personal variables. This approach culminated in comfort indices, such as PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), which supported global standards, including the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, as established in ASHRAE 55 (2017), and the International Organization for Standardization, as defined in ISO 7730 (2005) (Lamberts; Dutra; Pereira, 2014). However, by focusing on controlled environments, this approach neglects the complex dynamics of human behavior in response to thermal variations.

In this context, the adaptive approach to the study of thermal comfort emerges, presenting itself as a dynamic and contextual response to the limitations of traditional analytical models. Unlike the static approach, in which conditions are rigidly controlled in climate-controlled environments, the adaptive perspective recognizes the human capacity to actively adapt to the thermal conditions of the built environment (Monteiro, 2015).

The notable preference of occupants in naturally ventilated buildings for a broader range of conditions, in contrast to those in climate-controlled environments, highlights the decisive influence of the adaptive approach (Monteiro, 2015). Models like PMV, which disregard adaptive actions, may underestimate or overestimate individuals' actual thermal sensation, as pointed out by Humphreys and Nicol (2002).

In the normative context, both methods are present in ASHRAE 55 (2017). While PMV is intended for buildings with mechanical ventilation and artificial heating and cooling systems, the adaptive model is recommended for naturally ventilated buildings. This emphasizes the need to consider the specific dynamics of each building type in the pursuit of thermal comfort.

The adaptive model proposes a phenomenological perspective, emphasizing how people interact with their environment to achieve the desired thermal comfort. This paradigm recognizes three categories of adaptation involving physiological acclimatization mechanisms and occupants' behavioral and psychological processes to achieve appropriate thermal comfort (De Dear; Brager, 1998).

Experts and institutions, such as ASHRAE 55 (2017), recognize the influence not only of human physiology but also of behavioral and psychological aspects in the opportunities for adaptation to local environmental conditions (Monteiro, 2015). Although challenging to quantify accurately, these variables result in greater acceptance of higher indoor temperatures than predicted by PMV (De Dear; Brager, 2002).

The adaptive approach expands the thermal comfort zone, promoting higher levels of occupant satisfaction and significant energy savings. This paradigm's importance aligns with contemporary concerns about the environment and highlights the need for architectural designs that provide adaptation opportunities for occupants, going beyond specific normative limits (Monteiro, 2015). In a global context of climate change and increased environmental awareness, the adaptive approach emerges as a valuable guide for designing more sustainable and occupant-centered built environments.

In healthcare settings, architecture plays a crucial role in responding positively to environmental comfort, considering the two main protagonists of these environments: patients, whose physical and psychological conditions are affected, and staff, who are under high stress due to the nature of high-risk and responsible activities.

Therefore, it is essential that these facilities provide adequate ventilation and air circulation to meet thermal comfort requirements and, most importantly, to reduce the risk of aerosol-transmitted infections in hospital environments (Li; Tang, 2021). This discussion was reinforced during the recent global COVID-19 pandemic, which began in late 2019 and was caused by the SARS-CoV-2 virus. The risk of virus transmission is directly related to ventilation, as it can dilute the droplets and aerosols associated with the virus generated by infected individuals' coughing, sneezing, speaking, and breathing (Chen; Zhao, 2020).

Natural ventilation stands out as one of the ventilation strategies because it can provide high ventilation rates with energy efficiency and psychological benefits. However, in hospitals, not all environments are suitable for passive strategies due to their level of complexity and the risk of contamination by airborne external agents, which require specific and constant control of environmental variables (Brasil, 2010a).

In this sense, semi-critical areas and, especially, non-critical areas have great potential for natural ventilation. This aligns with the study by Short and Al-Maiyah (2009), in which the authors suggest that up to 70% of a hospital's usable area can be naturally ventilated, either partially or fully.

It is important to note that patients' perceptions of thermal comfort can vary, especially in specific health situations. Therefore, it is recommended that hospitals provide adaptation mechanisms, such as blankets, operable windows, fans and air conditioning, and blinds, among other strategies (Quadros, 2016).

In this context, this study aims to explore the application of the adaptive model from ASHRAE 55 (2017) in evaluating thermal comfort in naturally ventilated hospital environments at the University Hospital of the Federal University of São Carlos (HU-UFSCar), whose project was donated by architect João Filgueiras Lima. In Brazil, the architect is well-known for using natural ventilation and lighting strategies in his works, through comfort solutions that integrate functional, economic, and environmental principles. The HU-UFSCar is an architectural example that, even without the participation of the Rede Sarah Technology Center (CTRS), incorporates design strategies commonly used by the architect, offering a potential reference in the context of public hospitals.

The relevance of this study lies in the lack of specific investigations on thermal comfort in naturally ventilated hospital environments (Costa, 2022) and the recent COVID-19 pandemic, which highlighted the critical importance of effective ventilation in healthcare environments, where patient safety and comfort are priorities. Therefore, this research not only seeks to fill a gap in knowledge about hospital thermal comfort but also promotes a reflection on the relevance of the adaptive approach.

2. Method

This study adopted an empirical approach to analyze thermal comfort, conducting field experiments in naturally ventilated environments at the University Hospital of UFSCar, located in São Carlos/SP. During these experiments, measurements were taken of internal environmental variables, such as air temperature, globe temperature, air velocity, and relative humidity, simultaneously with the completion of questionnaires regarding users' thermal sensations and preferences.

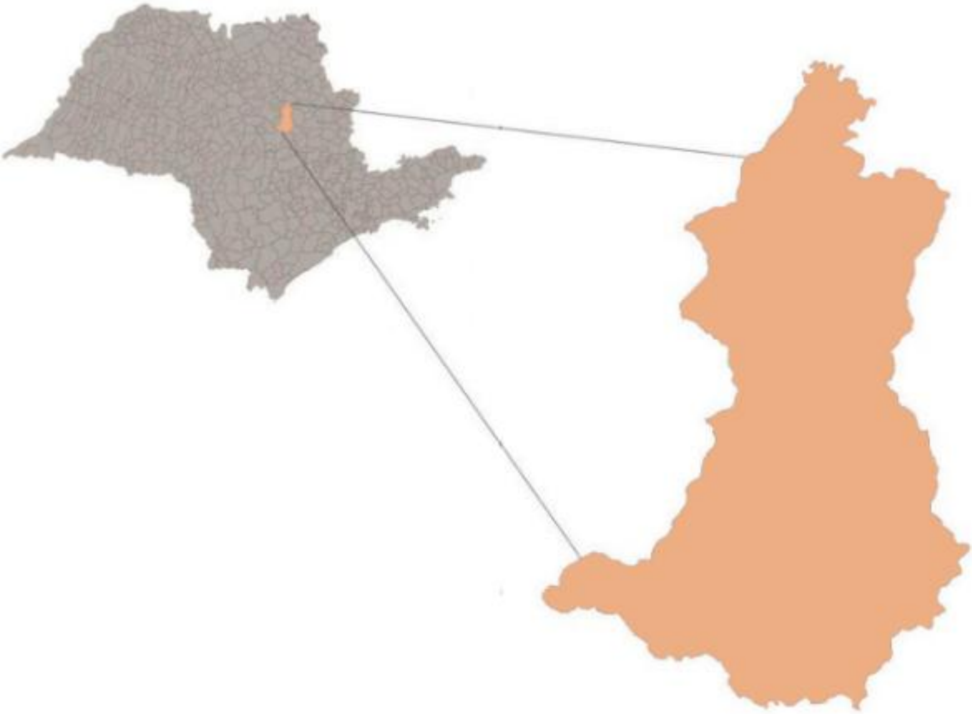
For the thermal comfort analysis using the adaptive model, the method outlined in the ASHRAE 55 (2017), proposed by De Dear and Brager (1998) and compiled by De Dear and Brager (2002), was applied. The analysis included establishing upper and lower limits for the Comfort Zone, considering an acceptability level of 80%, and identifying the number of degree hours in which the internal air temperature exceeded the comfort limits. The study also includes considerations about using adaptive opportunities during the analysis.

2.1. Characterization of the climate in São Carlos

São Carlos is a medium-sized city located in the geographical center of the State of São Paulo (Figure 1). Its latitude is –22.02°, its longitude is –47.89°, and its altitude is 844 meters, according to the Technical Report TR 15220-3-1 (ABNT, 2024b).

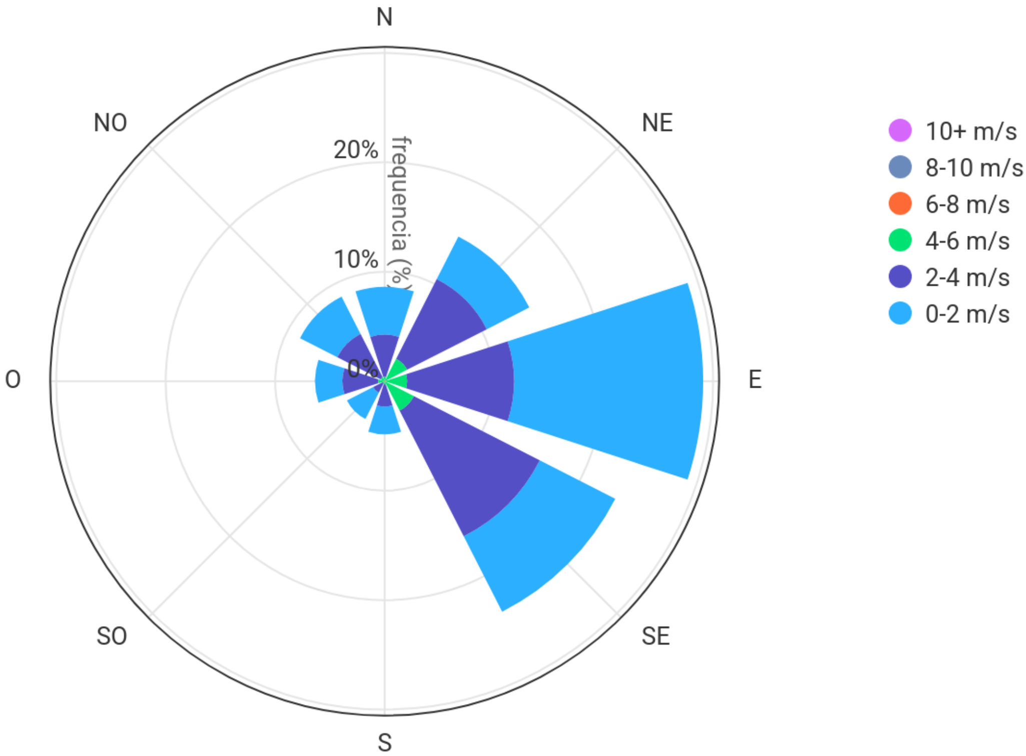
The region's climate is classified as Aw and Cwa according to the Köppen-Geiger system. The Aw type refers to a tropical climate with a humid summer and a dry winter, while the Cwa type characterizes a humid subtropical climate with a dry winter. According to climatological data for São Carlos provided by the National Institute of Meteorology (Brasil, 2010b), the temperatures in the city range from 24ºC to 28.5ºC for maximum temperatures and from 12.3ºC to 19ºC for minimum temperatures, resulting in an annual average of 20.6ºC. The relative humidity ranges from 62.3% to 80.2%, and the predominant winds come from the east and southeast, as shown in Figure 2.

Figure 1 – Location map of São Carlos



Source: Rampazzo and Sant'Anna Neto (2019), adapted by Costa (2022).

Figure 2 – Wind rose for São Carlos



Source: Universidade Federal de Santa Catarina (2025).

There is a dry season and a rainy season regarding rainfall. The driest months are April to September, accounting for only 20.10% of the total annual rainfall. On the other hand, January, December, and February account for 50% of the annual rainfall. Cloudiness, which influences the attenuation of sunlight, is more intense in January and December, while July and August show the lowest levels.

2.2. Object of study

The University Hospital of the Federal University of São Carlos (HU-UFSCar), which is the subject of this research, had its preliminary design donated by João Filgueiras Lima in 2004 to the Municipal Government of São Carlos, with the intention of being built by the Rede Sarah Technology Center (CTRS). However, a decision by the Federal Court of Accounts prevented the CTRS from providing the design outside the Rede Sarah. As a solution, the Municipal Government held a bidding process for the construction, adapting the project in collaboration with the Brasil Arquitetura and Apiacás Arquitetos offices (Costa, 2022).

Unlike the hospitals in the Rede Sarah, which specialize in treating the motor apparatus, the HU-UFSCar, dedicated to the medical course at the Federal University of São Carlos (UFSCar), offers comprehensive healthcare services. Despite the absence of CTRS involvement, the project stands out in hospital architecture by prioritizing natural ventilation and lighting, resorting to artificial lighting only when necessary.

The building incorporates strategies (Figure 3) such as sheds, tilting ceilings, underground galleries, vegetation, water mirrors, brise-soleils, and appropriate color choices, all of which optimize the use of natural resources like wind and sunlight and aim to reduce electricity consumption.

Figure 3 – Thermal comfort strategies of the UFSCar University Hospital

Source: Costa (2022).

However, due to a series of factors, primarily the fact that it is a public building, specific adaptations such as screens on the sheds, the installation of air conditioning, and the sealing of ceilings and shutters were implemented, resulting in a distortion of the original design, which had consequences for the hospital's thermal performance (Costa, 2022).

2.3. Analyzed environments

When analyzing passive thermal conditioning strategies, data collection was limited to naturally ventilated areas. The selection of environments for the experiment followed criteria based on the requirements of the ASHRAE 55 (2017) adaptive thermal comfort model, considering the context of the pandemic and the hospital's restrictions.

The selected environments meet the following criteria: a) they have operable openings accessible to users; b) they feature activities and clothing compatible with the demands of the adaptive model; c) there is no air conditioning in operation during the analysis days; d) the availability of occupants and space managers to collaborate with the research; e) environments with prolonged occupancy.

Due to design changes, a reduction in naturally ventilated spaces was observed. Five environments were selected for climate analysis based on the established criteria and the availability of measuring equipment. During the monitoring period, one point was installed in the basement, and three others were installed in the following internal environments: the main reception, the head office of the Diagnostic and Therapeutic Support Service (SADT), and the emergency reception. Spot measurements were also taken in the waiting area, and external data were obtained from the UFSCar Meteorological Station, located near the hospital.

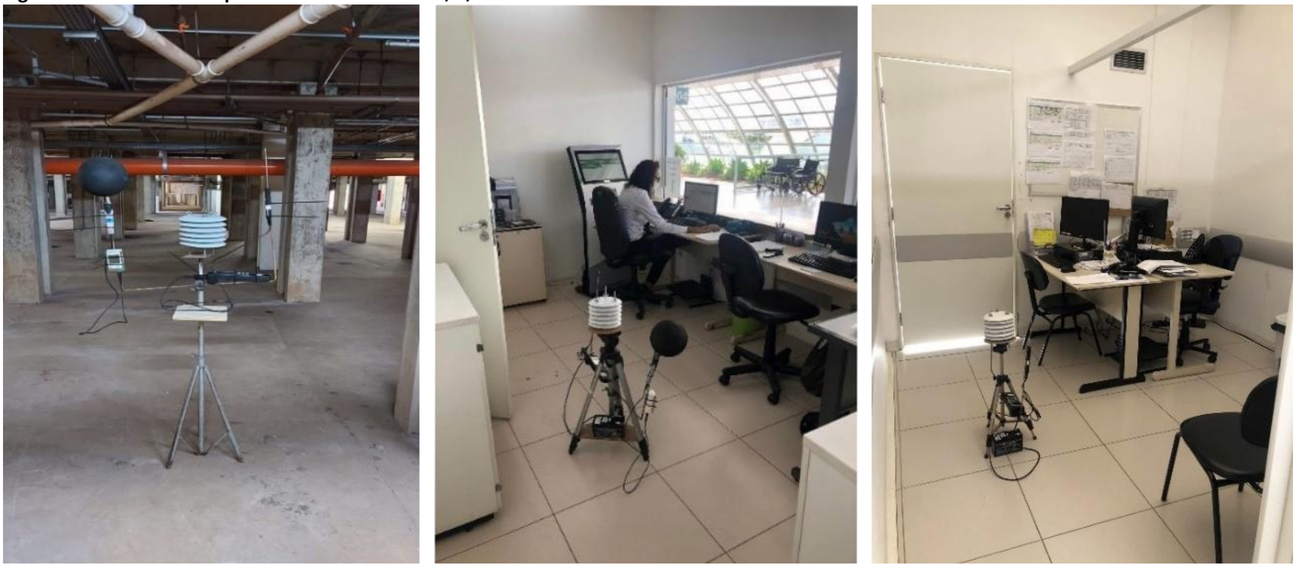
All the environments analyzed are in block B, the hospital's most active and completed sector (Figure 4). None of these environments are equipped with air conditioning; instead, they are ventilated through operable skylights, with the SADT also having Venetian blinds on the walls.

Environment 1 (Figure 5a) is located in the technical basement, near the openings of the water mirrors and under a ventilation duct, avoiding proximity to heat sources. Environment 2 (Figure 5b), representing the reception area, is located at the far left of the southeast face and features a fixed glass opening with small cutouts for communication. Its area is 14.35m², accommodating two to three employees, and it operates 24 hours a day in a 12-hour shift rotation. The head office of the SADT (Diagnostic Therapeutic Support Service), chosen as Environment 3 (Figure 5c), is located between other SADT rooms, covering an area of 8.6m², housing two employees, and operating for 12 hours.

Figure 4 – Thermal zones positioned on the floor plan of Block B of the HU-UFSCar

Source: Costa (2022).

Figure 5 – Measurement points in environments 1, 2, and 3 with the installed microclimatic station

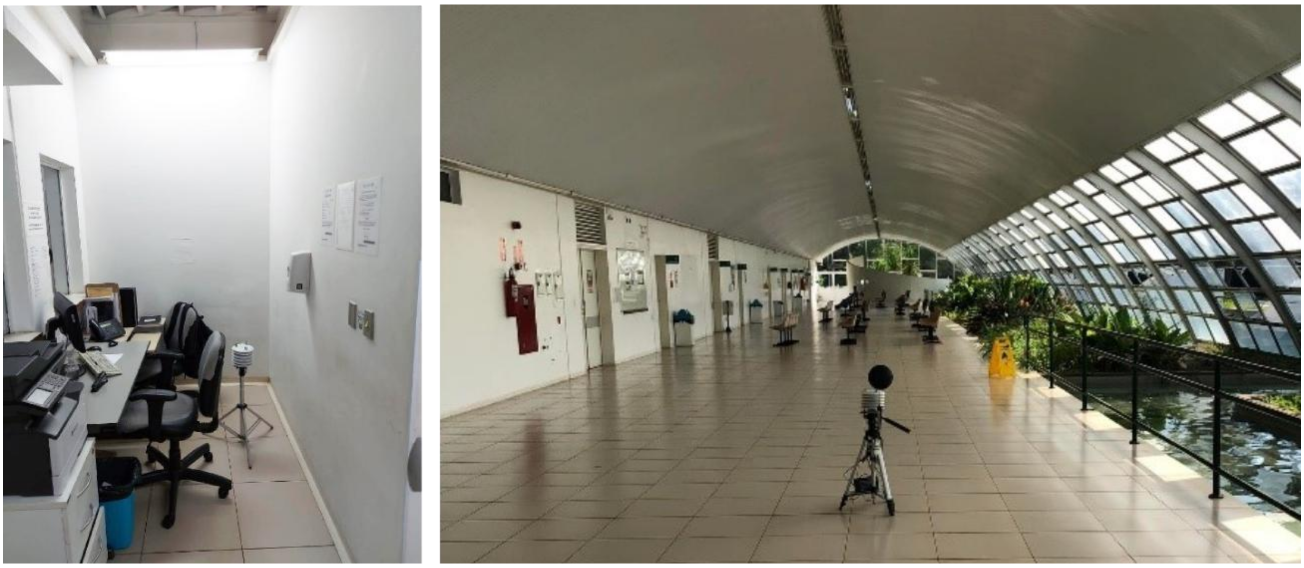


(a) (b) (c)

Source: Costa (2022).

The emergency reception is identified as Environment 4 (Figure 6a) and is located at the far right of the southeast facade, with openings facing the waiting area. Its area is 4.1m², accommodating only one employee on a 12-hour shift rotation during the 24-hour operation. The environment is not fully enclosed internally, as it has access to the corridor. Environment 5 (Figure 6b) is designated as the waiting area, where people wait before being attended to or proceeding to another location. This is the only space directly exposed to sunlight, with access to the southeast facade of the building, where the water mirrors, gardens, and the glazed facade are located.

Figure 6 – Measurement points of environments 4 and 5 with the installed microclimatic station



(a) (b)

Source: Costa (2022).

2.4. Measuring instruments

To analyze the thermal characteristics of the naturally ventilated environments in the hospital, four environmental variables that influence thermal comfort perception were measured: air temperature, globe temperature, air velocity, and humidity. Table 1 presents the technical specifications of the equipment used.

Five digital thermo-hygrometers with dataloggers, including the Onset brand HOBO H08-003-2 model (Figure 7a), were used for air temperature and humidity measurements. The air velocity measurements were conducted with four multifunctional devices equipped with a hot-wire probe, Testo brand, model 445 (Figure 7b). These instruments were positioned in all analyzed environments except for the emergency reception.

Two temperature dataloggers with NTC probes, Testo brand, model 175T2 (Figure 7c), were used for globe temperature measurements. One was placed in the main reception to represent the indoor environments, and the other was located in the technical basement. The absence of some instruments in certain environments is attributed to their limited availability at the time.

Table 1 – Technical specifications of the equipment used

Equipment	Brand/Model	Variable	Scale	Accuracy	Resolution
Thermo-hygrometer with Datalogger	Onset/HOBO H08-003-2	Air temperature and relative humidity	-20 até 70°C 25 até 95%	±0,7°C ±5%	0,38°C 1%
Multifunctional equipment with hot ball probe	TESTO/ Testo445 Probe	Air velocity	0 a +10 m/s	±(0,03 m/s + 5 % do vm)	0,1 m/s
Temperature datalogger with NTC probe	TESTO/175T2 with NTC immersion probe	Globe temperature	- 50 até 150°C	±0,5 % do vm (100 a +150 °C) ±0,2 °C (-25 a +74,9 °C) ±0,4 °C (*remaining range*)	0,1°C

Source: Costa (2022).

The measurements were conducted during February to represent summer conditions, considering the highest average and maximum temperatures recorded in this month according to the climatic norms of São Carlos (Brasil, 2010b). The equipment was installed on 02/02/2022 and removed on 25/02/2022. Air temperature and humidity were measured continuously, with readings recorded every 10 minutes over 24 hours. The spot measurements for air velocity and globe temperature were taken on 17, 18, 23, and 24/02/2022, including the hospital's waiting area from 7 AM to 7 PM.

Each monitored environment received a microclimatic station, with equipment positioned 0.60m above the floor, at the height of the abdomen for seated individuals, as ISO 7726 (1998) recommended. The placement was defined in collaboration with the staff to avoid interfering with activities, preferably in the center of each environment.

Figure 7 – Measurement instruments identified on the tripod

(a) (b) (c)

Source: Costa (2022).

Meteorological shelters were used to protect the air temperature sensors from the effects of solar radiation, in accordance with the recommendations of ISO 7726 (1998). These shelters were created in-house at the laboratory with the collaboration of other researchers, as documented in Barros, Costa, Mattia and Dornelles (2023).

2.5. Application of questionnaires

Questionnaires were administered simultaneously with spot measurements in the selected environments to collect personal and subjective variables. The questionnaire model is found in Appendix D of Costa's (2022) research and was based on Appendix K of ASHRAE 55 (2017). The questionnaires were divided into two parts: the first part included personal data, habits, and preferences related to thermal comfort, while the second part addressed the evaluation of the thermal environment, aiming to gather the participants' acceptability at different times of day and night.

The National Research Ethics Commission approved the research – CONEP (Project CAAE: 29370720.9.0000.5504, approved on 06/05/2020), and data collection only began after the CEP/CONEP system approved the project. Participants signed the Informed Consent Form (ICF) before completing the questionnaires. The questionnaire and the ICF were submitted and approved by CONCEP via the Plataforma Brasil.

As previously observed and discussed, the application times were defined based on the participants' dynamics, considering the time needed for adaptation to the environment, breaks, and shift changes. The adopted times were 08:30, 13:30, 17:30, 20:30, 01:30, and 05:30. Exclusively for the staff, the complete questionnaire was administered only at the first time slot. In contrast, at other times, an addendum was used asking for the thermal environment assessment. The responses were recorded and organized in an electronic spreadsheet for later analysis.

2.6. Data treatment

To analyze thermal comfort, the adaptive method from ASHRAE 55 (2017) was used. This method provides the internal temperature limits, enabling verification of whether the environment is within the acceptable range. For this, it was necessary to calculate the mean radiant temperature (MRT) from the globe temperature, as shown in Equation 1, to obtain the operative temperature, as shown in Equation 2, according to the simplified method of ASHRAE 55 (2017).

This equation is recommended for situations where the occupants have a metabolic rate between 1.0 and 1.3 met, with no direct solar radiation, air velocity below 0.2 m/s, and the difference between the mean radiant temperature and air temperature is less than 4°C. The exclusion of air velocity from the equation is justified because air velocity has minimal impact on the occupants' thermal sensation under the specific conditions where the equation is applicable.

$$t_r = \left[\left(t_g + 273\right)^4 + 0{,}4 \text{ x } 10^8 \left|t_g - t_a\right|^{1/4} \text{ x } \left(t_g - t_a\right)\right]^{1/4} - 273 \qquad (01)$$

where t_r is the mean radiant temperature (°C); t_g is the globe temperature (°C); t_a is the air temperature (°C), with:

$$t_0 = \frac{t_r + t_{ar}}{2} \qquad (02)$$

where t_0 is the operative temperature (°C).

Additionally, the prevailing mean outdoor temperature ($t_{mpa(out)}$), was also calculated, determined based on the seven days prior to the day in question, according to Equation 3 (ABNT, 2024a).

$$t_{mpa(out)} = 0{,}34t_{od-1} + 0{,}23t_{od-2} + 0{,}16t_{od-3} + 0{,}11t_{od-4} + 0{,}08t_{od-5} + 0{,}05t_{od-6} + 0{,}03t_{od-7} \qquad (03)$$

where t_{pmo} is the average temperature prevailing outdoors exterior (°C); t_{od-1} is the average temperature of the day prior to the day in question (°C); t_{od-2} is the average temperature of the day before the previous day (°C), and so on.

After obtaining such results, based on Equations 4 and 5, the upper and lower limits of the Comfort Zone were determined, considering an acceptability level for thermal comfort of 80%. Additionally, the number of hours the indoor air temperature exceeds the comfort limits of each environment was also identified, as well as the amount of degree-hours in discomfort.

Upper limit (ºC): $t_o = 0{,}31\ x\ t_{pmo}\ x\ 21{,}3$ (04)

Lower limit (ºC): $t_o = 0{,}31\ x\ t_{pmo}\ x\ 14{,}3$ (05)

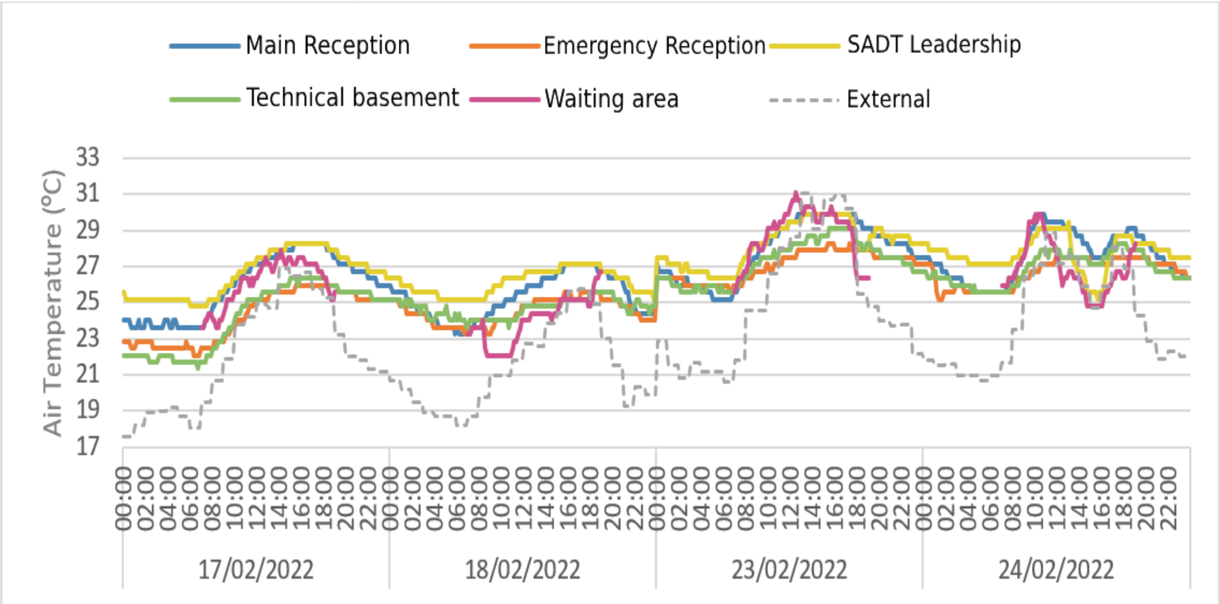
In summary, the criteria for applying this model include: outdoor average temperature between 10°C and 33.5°C; presence of operable windows accessible to the occupants; absence of mechanical cooling or air conditioning systems in the environment; possible heating system, provided it is not in use; occupant activity between 1.0 and 1.3 met; and the freedom for occupants to adjust their clothing, ranging from 0.5 clo to 1.0 clo, according to the internal and external thermal conditions (ASHRAE, 2017).

3. Results and discussion

3.1. Environmental and psycho-physiological variables

This article will present a section covering the period of spot measurements and questionnaires for an integrated analysis of these variables. As illustrated in Figure 8, the temperatures varied during this period, peaking on 23/02/2022. The main receptions and the SADT leadership generally recorded the highest maximum temperatures, while the waiting area surpassed the others on some hot days. The most significant thermal amplitude was observed in the main reception on the first days and in the waiting area on the last two days.

Figure 8 – Variation of air temperature (°C) on the days 17, 18, 23, and 24/02/2022

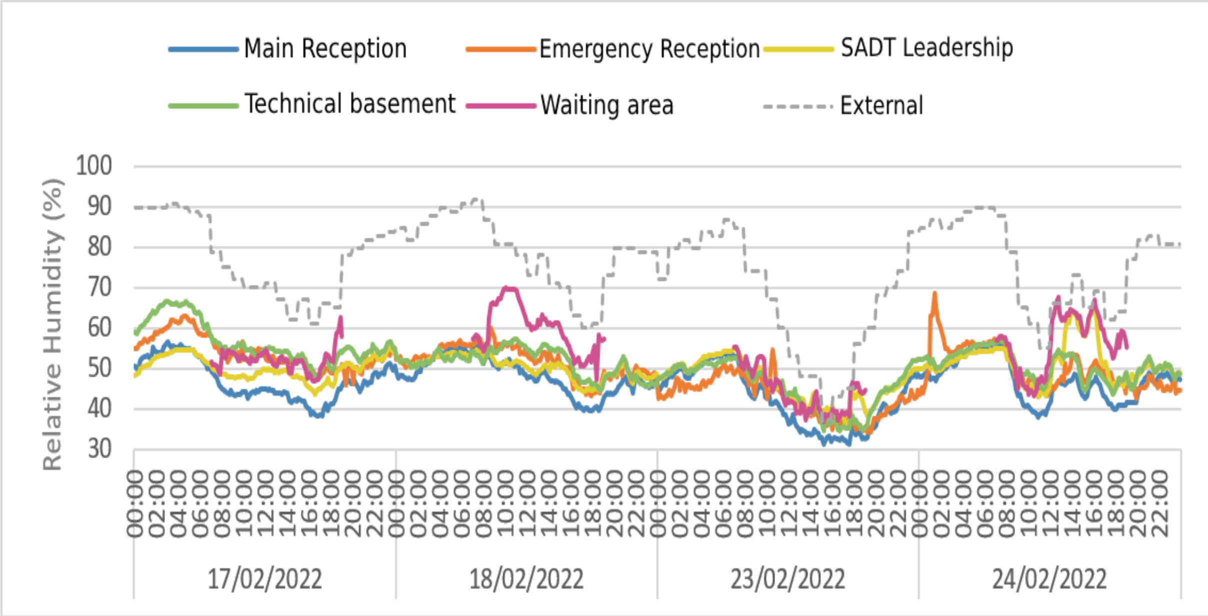


Source: Costa (2022).

The minimum temperatures varied across the environments, with the emergency reception being the mildest on the hottest days. The technical basement did not present the lowest temperatures expected, possibly due to the thermal inertia of the underground galleries.

In most environments, the relative humidity remained within the ranges recommended by NBR 7.256 (ABNT, 2022), from 40% to 60%, and by ASHRAE 55 (2017), from 30% to 60%. However, at specific times, particularly on the hottest day, the environments were outside the limits established by NBR 7.256 (Figure 9).

Figure 9 – Variation of relative humidity (%) on the days 17, 18, 23, and 24/02/2022

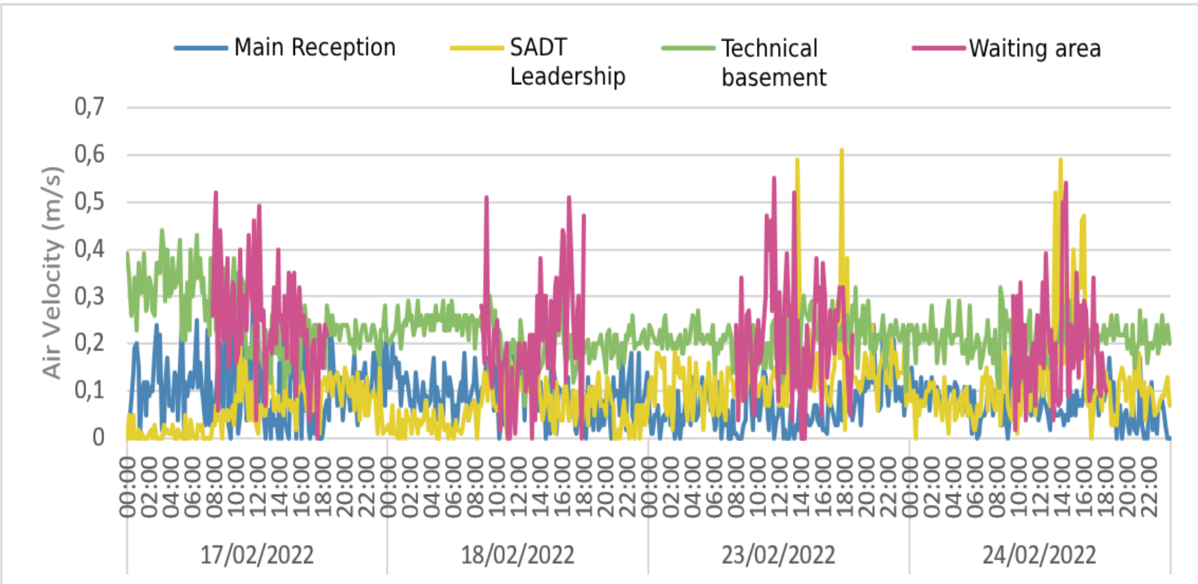


Source: Costa (2022).

Natural ventilation was less efficient in the SADT leadership and main reception, improving with fans on the last two days. The technical basement maintained a more stable air velocity, while the waiting area had the highest velocities due to natural ventilation from the glazed facade. However, as represented in Figure 10, the air velocities were considered imperceptible and did not provide a cooling sensation for the users.

During the four days of questionnaire application, 150 people participated, including 21 staff members, 84 patients, and 45 visitors. In the waiting area, 63.47% of the respondents were women, with an average age of 48, ranging from 19 to 85 years. The average height was 1.66m, and the average weight was 78.57kg. Most were born and reside in São Carlos, and 20.15% reported having had illnesses recently.

Figure 10 – Variation of air velocity (m/s) on the days 17, 18, 23, and 24/02/2022



Source: Costa (2022).

The majority of the staff in the analyzed environments were women (80%), with an average age of 35.6, ranging from 22 to 58. The average height was 1.67m, and the average weight was 62.49kg. Most were born in cities from the Southeast and Northeast regions, with São Carlos being the predominant city. The time working in these environments ranged from 1 month to 7 years, with an average of 3.5 years.

As for clothing, the reception staff wore pants, shirts, shoes, and socks, with a thermal insulation of approximately 0.67 clo. In the SADT sector, the attire consisted of pants, shirts, sneakers, socks, and lab coats, with thermal insulation of approximately 0.90 clo. Patients and visitors wore clothing with thermal insulation values ranging from 0.54 to 0.74 clo.

All participants were engaged in sedentary activities in the evaluated environment, with a metabolic activity level between 1.0 and 1.2 met, which aligns with the ASHRAE 55 (2017) guidelines for using the adaptive model.

The evaluation of thermal acceptability varied significantly across the analyzed environments. In the Table 2, the acceptability votes correspond to the results obtained from the questionnaires. At the same time, the ASHRAE 55 column complies with the standard's 80% temperature range based on the operative temperature at the time of voting and the calculated acceptability limits. The waiting area had the highest acceptability, while the SADT environments had the lowest, reaching only 13.3%. The receptions followed similar patterns, with votes distributed evenly. Notably, in the waiting area and main reception, the acceptance votes exceeded the upper limits of the ASHRAE 55 (2017) standard. However, in the emergency reception and SADT environments, there was a disparity between the votes and the environmental conditions in compliance with the comfort range of the standard.

When relating the acceptability votes to the average operative temperature, it was observed that temperatures between 25.27ºC and 27.87ºC in the waiting area received 94% acceptability. In the main reception, the highest acceptability occurred between 23.77ºC and 27.86ºC. The air temperature was used for the emergency reception and SADT leadership, where the operative temperature was not obtained. In the emergency reception, the highest acceptability occurred between 21.52ºC and 27.12ºC, while in the SADT leadership, there was almost no acceptability.

The analysis of natural ventilation strategies on days of high temperatures and high relative humidity revealed that, despite the building's design solutions, such as sheds and galleries, their effectiveness was limited under thermal stress conditions. On the hottest days, when the outdoor temperature exceeded 30°C and relative humidity surpassed 90%, natural ventilation failed to provide thermal comfort, especially in the SADT leadership areas and the main reception. In these areas, natural ventilation could not reduce internal temperatures significantly, and the increase in radiant temperature from the surfaces contributed to thermal discomfort, as indicated by the operative temperature measurements and thermal acceptability questionnaires.

Table 2 – Thermal acceptability votes and compliance with ASHRAE 55 (2017)

Environment	Acceptability Votes		ASHRAE Std. 55- 80%	
	Yes	No	Yes	No
Waiting Area	87 (73,10%)	32 (26,89%)	75 (63,02%)	44 (36,97%)
Main Reception	17 (62,96%)	10 (37,03%)	14 (51,85%)	13 (48,14%)
Emergency Reception	12 (54,40%)	10 (45,45%)	20 (90,90%)	2 (4,40%)
SADT	4 (13,30%)	26 (86,60%)	17 (56,60%)	13 (43,30%)

Source: Costa (2022).

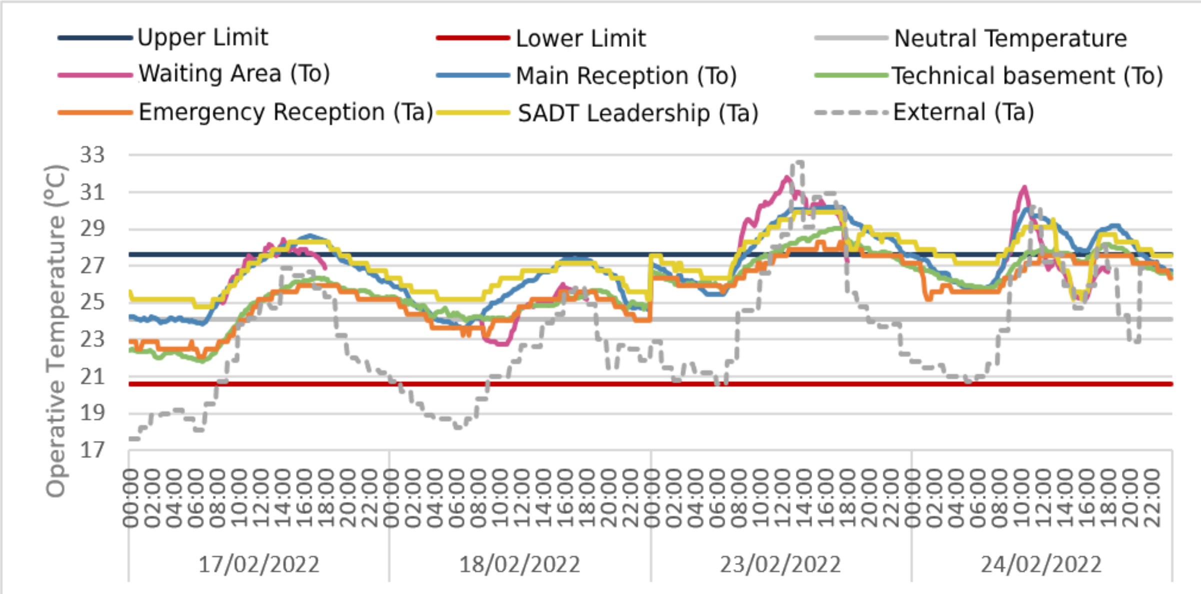
3.2. Thermal comfort limits by the adaptive model

The comfort limits were established through the adaptive model during the monitoring period. To determine the upper and lower temperature limits in the comfort zone, the prevailing outdoor air temperature was calculated for the seven days preceding the internal measurements. This procedure allowed for the determination of the neutral temperature and the lower and upper limits for 80% acceptability, which were fixed at 24.13ºC, 20.63ºC, and 27.63ºC, respectively.

Due to the lack of equipment, the globe temperature measurement was restricted to the waiting areas, main reception, and technical basement. In these areas, the average radiant temperature was close to the air temperature, resulting in an operative temperature similar to the air temperature, corroborating previous studies by Dantas (2015) and Ferreira (2019). Therefore, the operative temperature was calculated for these areas, while the air temperature was considered for the other environments.

The data regarding the upper and lower acceptability limits and the operative temperatures of the internal environments are graphically represented in Figure 11. It is possible to visualize the moments when the operative temperature of the environments exceeded the 80% acceptability limit established by the ASHRAE 55 (2017) adaptive model. The graphical analysis reveals that the highest and lowest outdoor temperatures recorded during the monitoring period were outside the comfort limit, indicating thermal discomfort.

Figure 11 – Acceptable thermal comfort zone for 80% of the people and operative temperature (°C) of the analyzed environments



Source: Costa (2022).

Concerning the internal environments, the waiting area experienced the highest discomfort hours proportionally to the total monitoring time. In this environment, the upper limit exceeded 17.3 hours out of 40.6 monitored hours, representing 42.6% of the hours, with an excess of up to 3.82ºC.

However, among the environments monitored for 96 hours, the SADT leadership area, followed by the main reception, had the highest discomfort. In the SADT leadership area, the upper limit exceeded 34 hours, corresponding to 35.41% of the hours and surpassing 2.60ºC. In the main reception, the upper limit exceeded 32.83 hours, representing 34.19% of the hours and exceeding 3.01ºC.

On the other hand, the emergency reception had the least discomfort hours, exceeding the limit by 6.83 hours out of a total of 96 hours, or 7.11% of the hours, with an excess of up to 1.01ºC. In the technical basement, the upper limit was also exceeded for a lesser amount of time compared to most environments, totaling 18.6 hours, or 19.37% of the hours, with an excess of up to 1.80ºC.

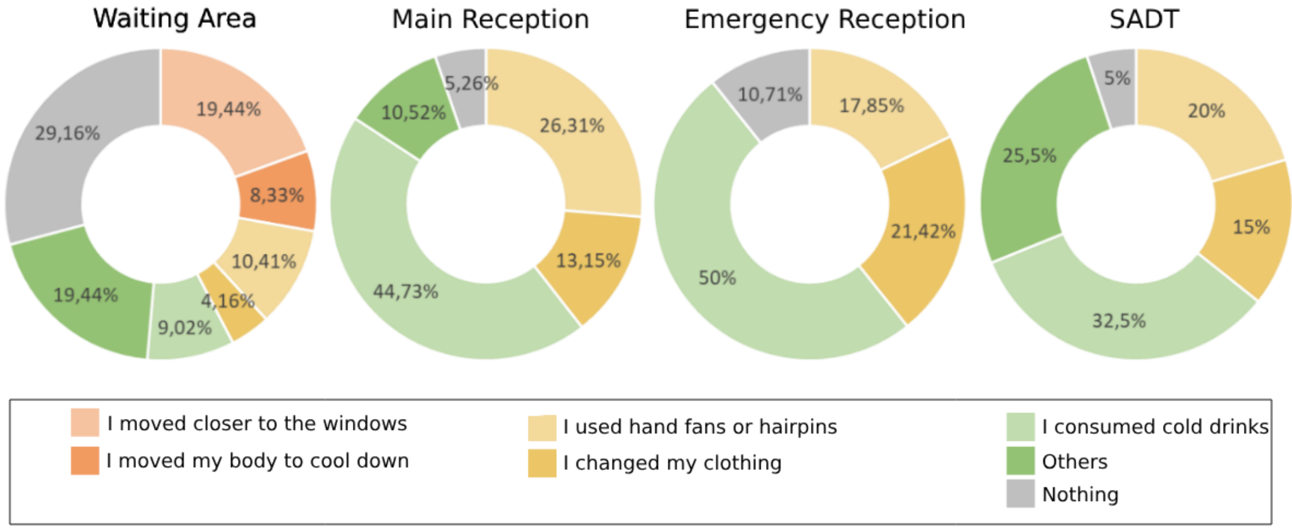
3.3. Thermal comfort limits according to the adaptive model

The questionnaire assessed the respondents' use of adaptive actions, as shown in Figure 12. Of the 129 patients and visitors, 67.44% adopted some form of adaptive action to improve thermal comfort, with the most common being moving closer to the windows. Almost all the staff reported using some adaptive action, with drinking cold beverages standing out as the most frequent. The use of hairpins and changes in clothing were also common in the SADT environments, especially due to the high proportion of women.

For the "other" option, actions like washing the face, leaving the environment, turning on the fan, and opening the room door to the waiting area were mentioned, with the latter being exclusive to the SADT leadership area. The "nothing" option seemed to be more prevalent among patients and visitors than among staff, possibly related to the amount of time these occupants spend in the environments and their limited autonomy over the space they occupy.

Several issues stand out regarding adaptive opportunities associated with passive thermal conditioning strategies. In the waiting area, the openings are not controllable, even by the staff, due to risks mentioned in the project changes. Most staff are unaware of how the tilt-up ceilings and Venetian blinds work, not operating them and expressing dissatisfaction with their effectiveness.

Figure 12 – Frequency of adaptive action



Source: Costa (2022).

Although most respondents said the Venetian blinds were open in the receptions, these strategies were not present in those environments. In the SADT areas where Venetian blinds exist, most reported them as closed or non-existent. As for the tilt-up ceilings, it was reported that they are rarely operated in all environments, and in the SADT area, the motorized system is inactive.

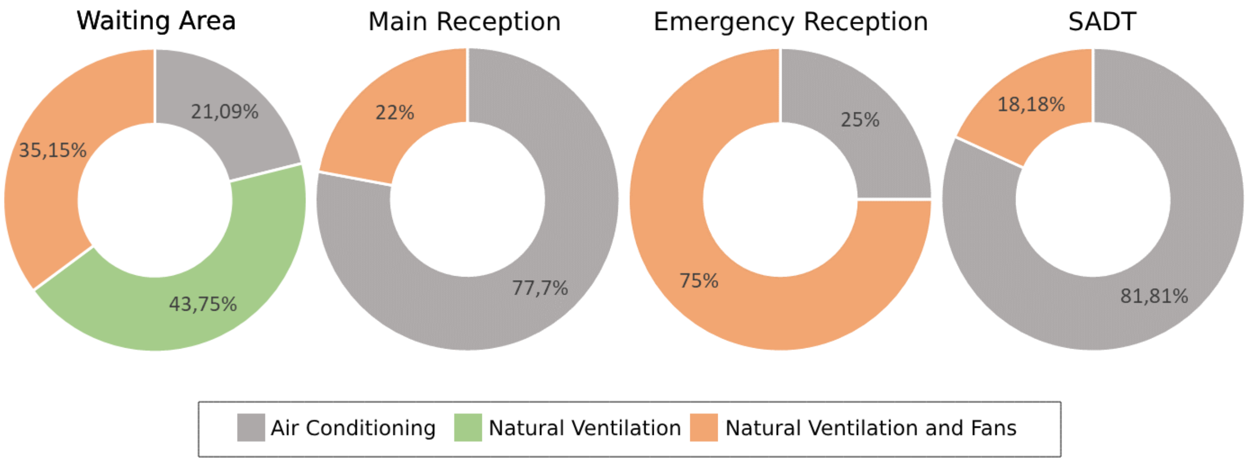
Reception staff claim that natural ventilation strategies do not work, especially on hot days with no airflow, resulting in extreme heat. SADT staff also question the effectiveness of these strategies, arguing that they are unsuitable for a hospital environment due to dust entering when the ceilings are opened. Additionally, they mention that the room becomes unhealthy on hot days, with no additional ventilation options, and uncomfortable on cold days.

For everyone, isolated natural ventilation is insufficient, requiring assistance from fans, as suggested by emergency reception staff, or replacing natural ventilation with air conditioning, a preference expressed by most reception staff and SADT environments.

On the other hand, natural ventilation, followed by the combination of natural ventilation and fans, are the most recommended strategies by patients and visitors, although some express discomfort with the environment's ventilation. Figure 13 presents the preferred thermal conditioning strategies by environment, while Figure 14 highlights the experience of respondents in air-conditioned environments. A relationship can be seen between the chosen strategy and the experience in air-conditioned environments, except for the main reception. As predicted by previous studies, such as Vecchi, Cândido and Lamberts (2016), regular exposure to artificially conditioned environments can influence people's thermal adaptability, making them less flexible regarding thermal comfort limits.

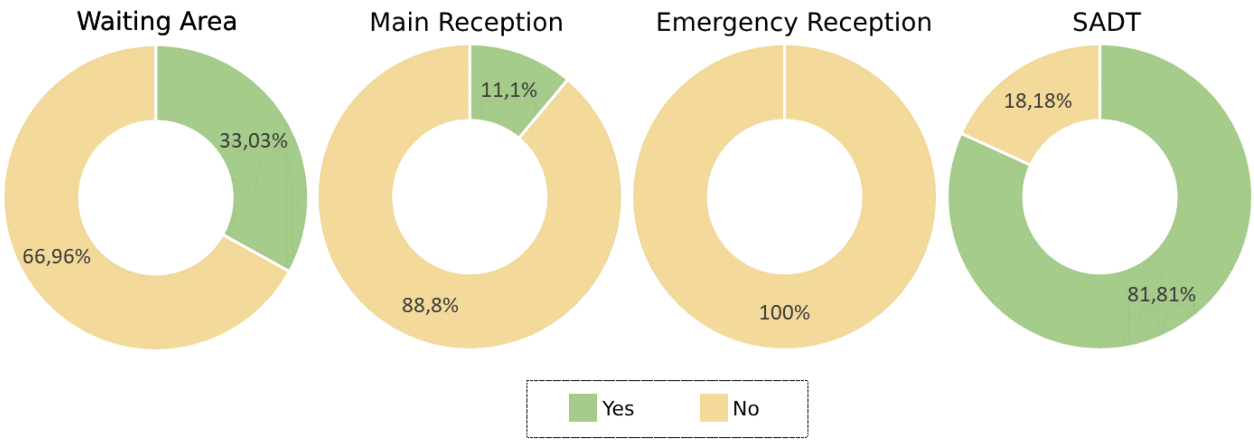
For everyone, isolated natural ventilation is insufficient, requiring the assistance of fans, as suggested by the emergency reception staff, or the replacement of natural ventilation with air conditioning, a preference expressed by most of the main reception staff and the SADT environments.

Figure 13 – Percentage of preferred thermal conditioning strategies



Source: Costa (2022).

Figure 14 – Percentage of experience in environments with air conditioning



Source: Costa (2022).

3.4. Critical analysis of the ASHRAE 55 adaptive method applied in hospitals in ZB4 in Brazil

The critical analysis of the ASHRAE 55 adaptive method applied in hospitals in Zone Bioclimatic 4 (ZB4) in Brazil reveals a series of challenges and complexities in evaluating thermal comfort in such specific and sensitive environments as hospitals. The significance of the differences between the questionnaire results and the limits calculated by the adaptive method lies in the need to understand to what extent the objective conditions established by the standard reflect the actual perceptions and needs of the occupants, especially in critical environments like hospitals.

This identified difference suggests that the adaptive method may not adequately capture the complexity of hospital environmental conditions, where specific equipment and activities can significantly influence perceived thermal comfort. Furthermore, patients' comfort may vary depending on their physical condition.

The discrepancy between the questionnaire results and the limits calculated by the adaptive method may also be attributed to the subjectivity inherent in the occupants' perception of thermal comfort. Individual preferences, past experiences, and personal expectations can significantly influence the evaluation of thermal comfort, which may not be fully captured by the standard's objective parameters.

Another important aspect to consider is the occupants' lack of control over environmental variables, such as the opening of windows and the operation of ventilation systems. This can lead to a disconnect between the objective conditions of the environment and the subjective perception of thermal comfort, contributing to the difference observed between the questionnaire results and the limits calculated by the adaptive method.

Furthermore, occupants' adaptation to environmental conditions over time may lead to an acceptance of thermal comfort levels outside the limits prescribed by ASHRAE 55. This highlights the importance of a more holistic and participatory approach to evaluating thermal comfort in hospital environments, which considers not only the standard's objective parameters but also the occupants' perceptions and needs.

4. Conclusion

This study proposed an empirical thermal comfort analysis in naturally ventilated environments at the University Hospital of UFSCar in São Carlos/SP. The primary goal was to analyze thermal comfort from the perspective of the adaptive thermal comfort model proposed by ASHRAE 55 (2017). The results obtained highlight not only the importance of respecting the limits established by the adaptive model but also the need to understand the occupants' adaptive practices and the limitations inherent in passive thermal conditioning strategies.

The measurements and questionnaires revealed that, during the analyzed period, all the examined environments exceeded the upper comfort limit. Generally, the acceptability votes showed a wider tolerance than the limits established by the ASHRAE 55 adaptive model (ASHRAE, 2017).

The results show that although natural ventilation strategies, such as sheds and galleries, are effective in mild climatic conditions, their ability to ensure thermal comfort is limited in high temperatures and humidity. These passive elements could not mitigate the effects of high radiant temperature and excessive humidity, especially during heat peaks, as indicated by the thermal acceptability questionnaires and operative temperature measurements.

Observing the adaptive actions users take to cope with adverse thermal conditions reveals the active search for thermal comfort. Moving to areas closer to windows was the most common action among patients and visitors, while employees frequently resorted to drinking cold beverages. However, the building offers employees more opportunities for adaptive actions, even though they do not always take advantage of them. Regarding hospitals, the thermal comfort patients feel may vary, especially in specific health contexts. Therefore, hospitals should implement adaptive measures to ensure more suitable thermal conditions.

The identified relationship between the choice of strategy and experience in air-conditioned environments highlights the influence of regular exposure to artificially conditioned environments on people’s thermal adaptability. Furthermore, the finding that some natural ventilation strategies were considered ineffective on very hot days emphasizes the need to evaluate the presence of these elements and the practical effectiveness perceived by users. The lack of knowledge about the operation of passive elements, such as tilt-up ceilings and shutters, indicates the need for educational programs or awareness campaigns to optimize the use of these strategies, thus promoting active participation by occupants in the pursuit of thermal comfort.

The adaptive approach of the ASHRAE 55 standard applied to hospitals in Bioclimatic Zone 4 of Brazil reveals significant challenges. The difference between the questionnaire results and the calculated limits highlights the complexity of hospital environmental conditions influenced by specific equipment and patients' health status. Furthermore, subjectivity in the perception of thermal comfort and the lack of control over environmental variables by occupants contribute to this disparity. A more holistic and participatory approach is needed to evaluate thermal comfort in hospitals more accurately.

These conclusions, which are more focused on the method and adaptive opportunities, emphasize the importance of flexibility in the design and management of hospital environments to meet users' dynamic needs regarding thermal comfort. This study not only sheds light on the complexities of thermal comfort in hospital environments but also promotes reflection on the relevance of the adaptive approach in the search for effective, user-centered solutions.

Declaration

The authors declare the use of generative artificial intelligence, specifically Grammarly, to enhance the English grammar and vocabulary throughout the text. After using this tool/service, the authors have reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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1 **Karime Zeferino de Souza Alves da Costa:** conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing-original draft, writing-review and editing. E-mail: tainagscosta@gmail.com

2 **Eduvaldo Paulo Sichieri:** conceptualization, project administration, supervision, writing-original draft, writing-review and editing. Address: Universidade Federal da Paraíba. Campus I, Castelo Branco, João Pessoa-PB. ZIP Code: 58051-900. E-mail: solange.leder@academico.ufpb.br