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Adaptive resilience of indoor thermal comfort in a mixed-mode office: An assessment under anomalous climatic conditions

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ABSTRACT

Climate anomalies linked to a changing climate increasingly challenge buildings to maintain comfortable indoor environments without excessive energy use. This study assessed physiological, behavioral, and perceptual responses of occupants in a mixed-mode office during an anomalous year in a subtropical region, which caused hotter-than-average conditions in typically mild seasons. In a year-long living-lab experiment, indoor environmental variables, HVAC use, clothing insulation, thermal perceptions, and physiological signals of 21 participants (12 females, 9 males) were monitored to examine adaptations to these anomalous conditions. Hotter-than-average days elicited higher mean and localized skin temperatures, particularly during outdoor exposure during lunch breaks. Occupants also adopted behavioral strategies, mainly reducing clothing insulation and adjusting building systems to reach higher air velocity levels. Indoor thermal perceptions varied under hotter outdoor conditions; however, the magnitude of this shift depended on the analytical direction adopted in the regression modeling. When thermal sensation was treated as the response variable to indoor conditions, the analysis indicated a notable reduction in neutral SET (-1.12 °C) during hotter days, whereas treating indoor conditions as the response to thermal sensation resulted in a minimal shift (+0.12 °C). Overall, the findings suggest that buildings can maintain comfortable conditions under climate anomalies when occupants are provided with meaningful adaptive opportunities. Incorporating building interfaces that enable adaptive opportunities, promoting flexible clothing adjustments, and applying adaptive comfort principles are essential for enhancing both building and human resilience in a warming and increasingly variable climate.

1. Introduction

The 2023–2024 El Niño anomaly produced significant climatic deviations across Latin America. According to the World Meteorological Organization, El Niño conditions in the second half of 2023 intensified climatic extremes throughout the region, increasing environmental and sectoral risks [1]. El Niño results in regionally diverse impacts on precipitation and temperatures observed in South America, with associated socio-economic impacts across the region due to consequent extreme events [2]. In Brazil, 2023 ranked among the warmest years in INMET's historical record, marked by nine heat waves attributed to the combined effects of global warming and El Niño [3]. In southern Brazil, INMET bulletins documented the intense rainfall typically associated with strong El Niño events, while EPAGRI/CIRAM [4] and INMET [3] recorded out-of-season heat as early as August 2023, with unusually high maximum temperatures.

Although the broader climatological effects of El Niño are well established and studied, the influence of anomalous conditions on indoor thermal comfort remains insufficiently documented. As noted by Djamila [5], few field studies in the ASHRAE database were conducted during anomalous periods, suggesting that existing adaptive comfort models may underrepresent conditions shaped by anomalous weather. Studying thermal comfort during an event of this magnitude, therefore, provides an opportunity to examine human adaptive responses, encompassing both involuntary physiological adjustments and deliberate behavioral strategies. Such an approach may also help advance adaptive comfort discussions toward a deeper understanding of human resilience to climate anomalies.

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To capture responses under real-world conditions, including seasonal variability and extreme events, living labs constitute an appropriate methodological approach. Unlike test chambers, where experiments occur under tightly controlled conditions, field studies and living labs preserve the complexity of everyday use and the degrees of control exercised by occupants, strengthening the external validity of inferences [6,7]. When such an approach is implemented in mixed-mode buildings (i.e., where natural ventilation and mechanical air-conditioning alternate [8]), it becomes possible to observe how occupants engage with the adaptive opportunities highlighted in recent mixed-mode research [9]. Indeed, as the control of windows under natural ventilation depends on a variety of influences [10], indoor air velocity adjustments through window operations may also help occupants to cope with hotter-than-expected seasonal exposures.

Outdoor climate exerts a first-order control over indoor thermal conditions, especially in buildings that rely partially or entirely on natural ventilation. Despite its advantages for building energy efficiency and the benefits promoted by ventilation, natural ventilation increases susceptibility to climatic variability and extremes because indoor environments remain strongly coupled to outdoor conditions [11]. This coupling can compromise thermal comfort during heat waves, humidity spikes, and atypical seasonal transitions, particularly when opportunities for occupant control were not specified to accommodate such demands. In periods of anomalous climate events, the interplay between exposure and alliesthesial responses becomes relevant to understand adaptive behaviors and comfort resilience [12].

Within this context, adaptive thermal comfort theory explains how occupants manage climatic variability through physiological acclimatization and behavioral adjustments [13]. Previous field studies in mixed-mode buildings in Florianópolis, southern Brazil, indicated the applicability of adaptive comfort frameworks in this scenario. Behavioral adaptations in terms of clothing adjustments represented a common action to cope with temperature fluctuations in both offices [14] and university classrooms [15]. However, individual differences and cultural traits also influence adaptive behaviors in mixed-mode buildings [16]. The literature also supports that mixed-mode buildings can provide a better balance and result in higher thermal comfort levels for occupants, whether males or females, compared to fully air-conditioned buildings [17]. As a consequence, MM buildings resulted in higher levels of thermal comfort being reported by their occupants, emphasizing that wider ranges of temperatures are not necessarily linked with thermal discomfort [18].

Despite meaningful advances, the dynamic of human adaptation to climate anomalies in real-world buildings remains elusive. Several gaps persist: (i) few studies track buildings across a year dominated by climatic anomalies, limiting understanding of adaptive processes under these conditions; and (ii) the integration of physiological and behavioral adaptations in real environments remains limited, constraining our grasp of how external anomalies propagate indoors and shape comfort perceptions and actions. Therefore, the primary aim of this study is to understand human psychophysiological and behavioral responses to indoor conditions over a year marked by a climatic anomaly in a mixed-mode living laboratory located in Florianópolis, southern Brazil. Physiological (e.g., skin temperatures over the body) and behavioral adaptations (e.g., clothing insulation) are documented, as well as thermal perceptions are collected during full days of experiments.

2. Method

This section presents the methodological procedures adopted in the study. It first describes the regional climate and the characteristics of the research site, situating the building and its characteristics. Next, it details the monitoring campaign, specifying the indoor environmental variables and the physiological signals recorded, along with the instruments and data-collection protocols. The occupant surveys and the monitoring of environmental conditions are then presented, including sampling criteria and temporal windows. Finally, the data analysis procedures are outlined, such as the statistical tests, in order to ensure reproducibility and coherence in the interpretation of results.

2.1. *Climate description*

This study investigates indoor thermal comfort in an office located in Florianópolis, southern Brazil. The region's climate is classified as Cfa according to the Köppen-Geiger system [19] and 2A by ASHRAE 169 [20], characterised by subtropical conditions with high humidity and warm summers.

This location lies within the influence of El Niño, the warm phase of ENSO (El Niño-Southern Oscillation, an ocean-atmosphere coupled mode). Operationally, El Niño is defined by sustained anomalous warming of sea-surface temperatures in the central-eastern equatorial Pacific, together with coherent atmospheric changes in winds, convection, and sea-level pressure [21,22]. From June 2023 to March 2024, a moderate-to-strong El Niño prevailed based on the ONI (Oceanic Niño Index). In southern Brazil, the setting of this study, this ENSO phase increases the likelihood of positive temperature anomalies and episodes of heavy precipitation [23].

To characterize the prevailing weather conditions during the monitoring campaign, a representative day was defined for each of the four seasons. Each representative day was constructed using meteorological data corresponding to the experimental days within the respective seasonal monitoring periods. The summer period included 13 experimental days, distributed between February 3 and March 2. The autumn period included 14 experimental days, distributed between May 22 and June 16. The winter period included 13 experimental days, distributed between July 10 and 26, and the spring period included 12 experimental days, distributed between October 3 and 25.

Hourly median values of meteorological parameters, including air temperature, relative humidity, solar radiation, and cloud cover, were used to describe the representative days for each monitoring period. Fig. 1 presents the corresponding meteorological profiles. Air temperature, relative humidity, and solar radiation data were obtained from the INMET weather station in Florianópolis, while cloud cover data were sourced from the airport weather station’s historical records [24].

As shown in Fig. 1, summer exhibited the highest outdoor air temperatures and solar radiation, with mean maximum values approaching 30 °C and midday radiation reaching nearly 1000 W/m^2, respectively. Autumn presented the largest diurnal temperature range, with differences of almost 10 °C between the daily minimum and maximum. Both summer and autumn were characterized by predominantly clear skies. While winter and spring representative days were mainly overcast. Winter displayed the lowest temperatures (daily mean around 18 °C), as expected for the season, while the spring profile was similar to winter but slightly warmer (daily mean around 20 °C). Relative humidity showed little variation across seasons, consistently remaining above 80 % throughout the year, with minimum values of approximately 60 % during summer and autumn, particularly during the warmest hours of the day.

2.2. *Living lab characteristics*

The experimental facility consists of a living lab incorporating two meeting rooms, two individual offices, a kitchen, and a shared open-plan area containing 36 workstations. The living lab is located on the top floor of the Civil Engineering building at the Federal University of Santa Catarina (UFSC). Typical office activities occur in the shared area, where the experiments were conducted (as highlighted in Fig. 2). During the experiments, participants were allowed to perform their regular activities, including operating windows, the HVAC system, and personalized environmental control systems (PECS). Thermal PECS available at the laboratory include small desk fans and evaporative coolers. The HVAC system consists of five air conditioners distributed across the open-plan

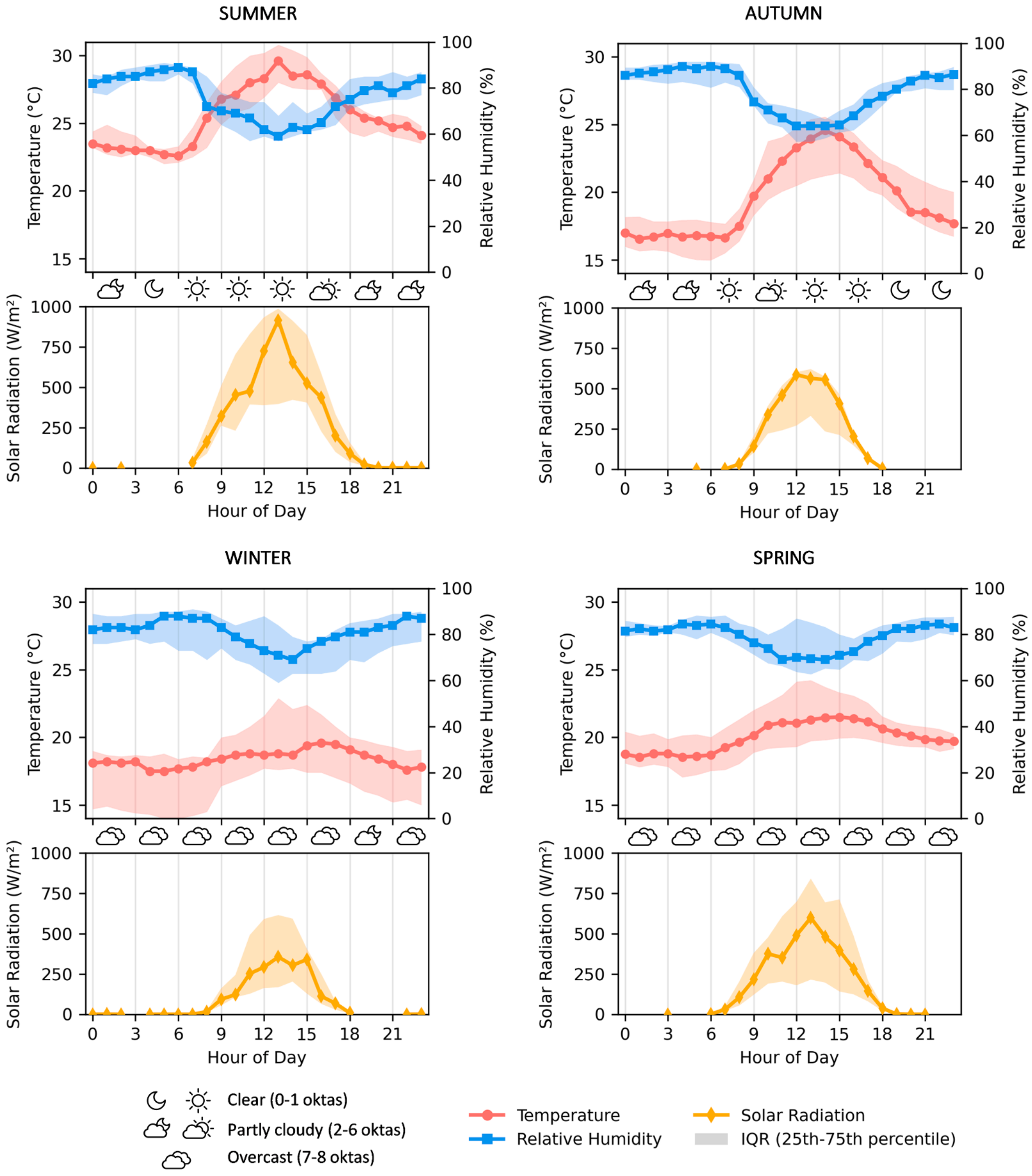

Fig. 1. Representative days for each monitoring period.

office.

2.3. *Monitoring campaign*

The monitoring protocol was carried out daily from 09:00 to 12:00 and from 13:30 to 16:00, covering typical morning and afternoon working hours. The protocol did not include environmental or perceptual measurements for periods spent outside the office during lunch. To minimize potential effects of outdoor exposures, all participants were present in the shared office at least 30 min before the start of each morning and afternoon session. It included physical indoor measurements and survey applications every 30 min throughout the day. Experimental measurements were conducted across all seasons: summer (February 3–March 2), autumn (May 22–June 16), winter (July 10–26), and spring (October 3–25). The study protocol was approved by the Research Ethics Committee Involving Human Subjects (CEPSH-UFSC), under the ethics approval number 69.823.523.7.0000.0121. All participants provided informed consent prior to participation. Data were anonymized, and participation was voluntary, with the option to withdraw at any time.

2.3.1. *Indoor environmental variables*

The immediate microclimate at the workstations of each daily group of coworkers was characterized by measuring globe temperature, air (dry-bulb) temperature, air velocity, and relative humidity at adjacent locations. Air and globe temperatures were monitored at a height of 0.60 m, positioned laterally to the participant with a horizontal offset of approximately 0.40–0.50 m (Fig. 3). Mean radiant temperature was derived from the globe temperature. Variables were recorded using a Testo 400 universal climate instrument mounted on a tripod and equipped with a temperature, humidity probe, an omnidirectional air-velocity sensor, and a 150-mm black-globe thermometer, described in Table 1. Each participant remained at their typical workstation, and participants who normally sat near one another were grouped so that the sensor could be placed centrally among them. As a result, each experimental day involved groups of 3–4 adjacent participants.

2.3.2. *Participants*

Across all seasons, 21 participants were enrolled, with each completing two to four sessions in at least one season. Of these, 12 were female and 9 were male. Female participants had a mean height of 165 ± 6.6 cm, a mean weight of 59.9 ± 7.3 kg, and a mean age of 32 ± 8

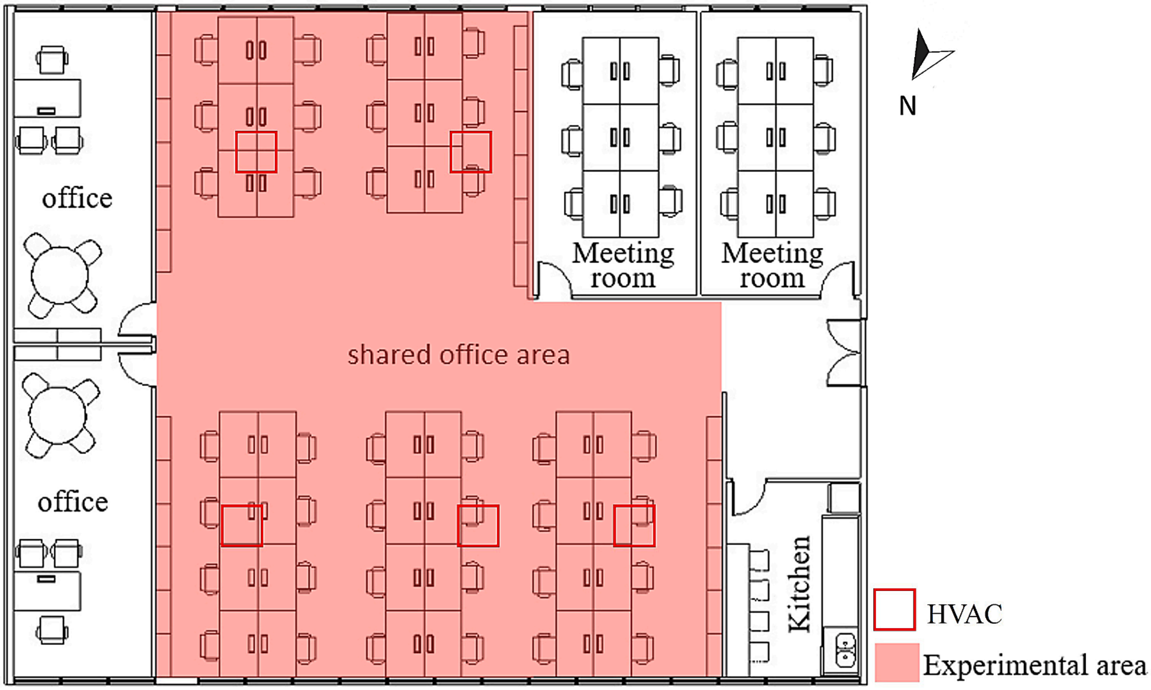

Fig. 2. Shared office area of the living lab where the experiments were conducted.

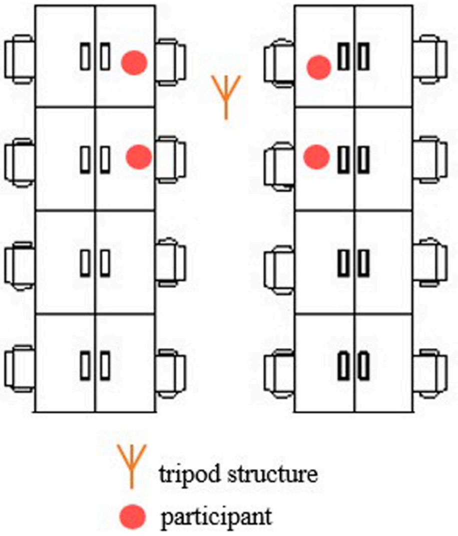

Fig. 3. Tripod structure located between worktables and close to the participants.

Table 1
Equipment characterization.

Equipment	Environmental Variable	Resolution	Accuracy
150mm Globe Probe, Type K Thermocouple	Tglobe [°C]	0.1 °C	Class 1[1]
TC Type K	Tair [°C]	0.1 °C	± 0.5 °C
Sensu	Vair [m/s] and RH [%]	0.01 m/s | 0.1 %	3 %

[1] The accuracy of Class 1 refers to -40 to +1000 °C (Type K).

years, contributing a total of 1008 responses. Male participants had a mean height of 176 ± 7.2 cm, a mean weight of 78.0 ± 7.7 kg, and a mean age of 29 ± 3 years, contributing a total of 778 responses.

2.3.3. Physiological signals

Monitoring of physiological variables (skin temperature and heart rate) was also included in the protocol. Skin temperature was recorded using Thermochron iButton sensors (resolution 0.0625 °C) at 60-s intervals. Sensors were placed at ten body locations following the method 10c, and mean skin temperature was calculated using Eq. (1), described by Liu et al. [25], which has been shown to provide high reliability and sensitivity for calculating mean skin temperatures. Heart rate was measured using a Polar H10 chest strap and, as a backup in case of missing data, a Polar A370 wrist device worn on the participants' left wrists (Fig. 4).

$$\begin{aligned} MST = {} & 0.07T + 0.13Q + 0.19O + 0.12M + 0.12K + 0.12J + 0.05H \\ & + 0.06F + 0.08D + 0.06A \end{aligned} \tag{1}$$

Where: T - Skin temperature of right foot;
Q - Skin temperature of anterior calf;
O - Skin temperature of anterior thigh;
M - Skin temperature of left abdomen;
K - Skin temperature of left chest;
J - Skin temperature of left back;
H - Skin temperature of right hand;
F - Skin temperature of left forearm;
D - Skin temperature of right upper arm;
A - Skin temperature of forehead.

2.3.4. Questionnaires adopted in the research

Participants completed online questionnaires every 30 min throughout the workday. The questionnaire was divided into sections: anthropometric and behavioural patterns (14 questions), sensitivity (3 questions), and thermal perception and comfort (15 questions). The full questionnaire is presented in Appendix A. Anthropometric and behavioural questions were answered only during the first participation of the day, while subsequent responses focused on comfort and thermal perception. For this study, the analysis specifically focuses on thermal sensation and clothing insulation (clo). Thermal sensation was assessed using a 7-point ASHRAE-type scale ranging from "–3 (cold)" to "+3

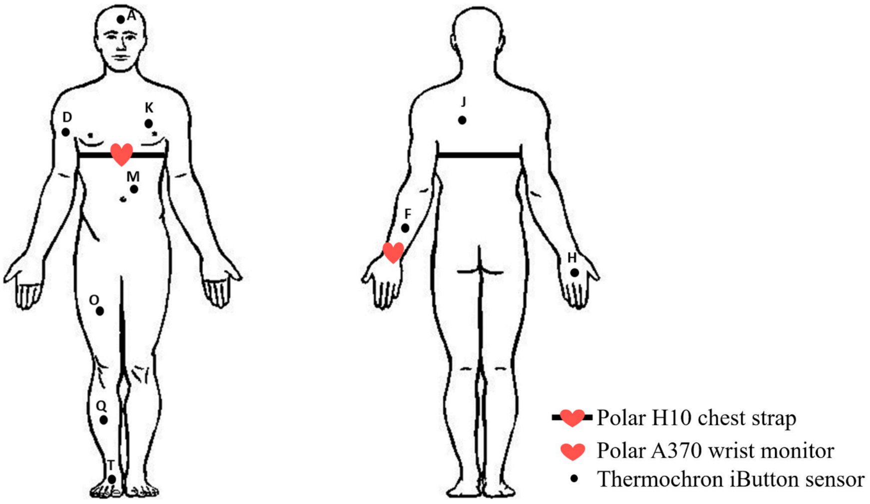

Fig. 4. Overview of the 10 skin measurement locations and the polar H10 chest strap. adapted from Liu et al. [25].

(hot)". Thermal preference was measured with a corresponding 7-point scale, from "–3 (much cooler)" to "+3 (much warmer)," with 0 indicating "no change". Clothing items were self-reported using multiple-choice checklists for upper-body garments (e.g., sleeveless tops, T-shirts, long-sleeve shirts, sweaters), lower-body garments (e.g., thin trousers, thick trousers, shorts, skirts), one-piece outfits (e.g., dresses, overalls), and footwear (e.g., socks, shoes, boots, sandals). These items were later used to estimate total clothing insulation (clo), based on ASHRAE 55 insulation values [26]. A detailed list of clothing components was designed to minimize uncertainty when categorical options of clothing insulation were provided for occupants to choose from. However, even with a detailed list, clothing insulation estimates remain subject to uncertainty and self-reporting bias, as precisely quantifying clo values is challenging in real-world studies when standardized ensembles are not provided.

2.3.5. Mixed-mode building operation and control strategy

The HVAC monitoring system recorded the operational status of all five air-conditioning units in the open-plan office, including setpoints, operating modes, airflow velocities, and flow directions. The units were locally controlled by occupants, with no hierarchical control, centralized automation, or adaptive setpoint optimization. Although configured on the same control panel, each unit could be operated individually or collectively.

Window operation was unrestricted and not interlocked with the air-conditioning system, reflecting typical mixed-mode practice in Brazilian office buildings. In practice, when occupants opened the windows, they also turned off the AC units, and closed the windows when the units were on. Operational data collected during the experimental days were used to identify occupant adaptive behaviors related to HVAC use.

2.4. Data preparation and analyses

2.4.1. Classification of days according to the outdoor conditions

To examine the influence of typical and atypical thermal conditions on participant responses, the 2023 experimental days were systematically classified into two categories: hotter than average and cooler than average. A historical baseline was established using outdoor air temperature data recorded between 2013 and 2023 [27]. The 2013–2022 period was used to calculate the historical mean outdoor air temperature for the periods corresponding to the 2023 experimental campaigns in each season, providing a climatological reference for typical conditions at that time of year. The 2023 outdoor air temperature was then compared to these historical averages to classify each experimental day as hotter or cooler than average.

The daily mean outdoor air temperature was selected as the most representative indicator of prevailing thermal conditions. This choice was based on several considerations. First, air temperature data provide the most reliable historical record, given their continuity and accuracy in meteorological monitoring compared to other variables such as solar radiation or wind speed, which are often affected by instrumental gaps or site-specific exposure issues. Second, relative humidity in Florianópolis remains consistently high throughout the year (annual mean >80 %), exhibiting limited daily and seasonal variability (see Section 2.1); consequently, its contribution to differentiating anomalous days is marginal.

Within each season, days were classified as hotter than average when the daily mean temperature exceeded the historical mean for that period. According to this criterion, 7 of 13 experiment days (54 %) were categorized as warmer in summer, 12 of 14 days (86 %) in autumn, 8 of 13 days (62 %) in winter, and 4 of 12 days (33 %) in spring. This classification formed the basis for subsequent analyses of thermal perception throughout the year. Table 2 presents the seasonal mean daily air temperature and the number of responses for each classification, as the number of participants varied across experimental days. A total of 960 responses were collected on hotter-than-average days and 826 on cooler-than-average days throughout the year. Importantly, outdoor-based labels are not treated as direct indoor conditions in this study, but as contextual boundary conditions under which indoor adaptation and operation occur in the mixed-mode office.

2.4.1.1. Consistency of hotter/cooler classifications. Thermal conditions extend beyond air temperature alone; however, daily means can mask important variation. To account for this, days were reclassified as hotter-than-average or cooler-than-average using two alternative outdoor metrics: daily mean apparent temperature ("AT") and daily maximum air temperature ("Max"), in addition to our primary metric, daily mean

Table 2
Responses per thermal classification and season, with historical average air temperature reference.

Variables		Seasons		
	Summer	Autumn	Winter	Spring
Historical average air temperature (°C)	25.2	18.0	17.1	20.4
Responses on hotter-than-average days	211	374	275	100
Responses on cooler-than-average days	209	80	212	325

outdoor air temperature ("Mean"). Apparent temperature was calculated from weather data, including outdoor air temperature, relative humidity, and wind speed, using the pythermalcomfort library in Python. Analogous to the primary exposure (Mean), seasonal thresholds for the historical average were calculated from the previous 10 years (2013–2022) of outdoor weather data for each season; for Max, the historical average was defined as the mean daily maximum air temperature over the same period.

To assess the consistency of the hotter/cooler classification across these outdoor metrics (Mean, Max, and AT), we compared the categories assigned by each method using percentage agreement (Table 3). The agreement is measured simply by the match between days and classifications (hotter or cooler than average). Overall, agreement between methods was high, with annual percentage agreement above 83 % across all metric pairs. The highest correspondence (93 %) was observed between Mean and AT in autumn, whereas the lowest agreement (69 %) occurred between Mean and AT in summer. The higher discrepancies are limited and mainly occur on days when metrics are closer to the threshold.

Since the agreement between classification methods was strong, indicating that alternative metrics would produce similar outputs, we retained the Mean method for all subsequent analyses. This choice reflects the higher confidence in air temperature weather data relative to wind speed, as well as the widespread use of mean temperature as the standard metric for historical climate comparisons.

2.4.2. Physiological adaptations

The analysis of skin temperature (MST) dynamics was performed in several structured steps. First, the dataset was chronologically sorted by day, participant (ID), and timestamp to ensure correct temporal ordering of measurements. Next, an artifact exclusion procedure was applied to remove abrupt changes likely caused by measurement errors (i.e., rapid changes of |1 °C| within 1 min). Scientific literature shows that threshold-based or filter-based artifact removal is a common preprocessing approach in wearable physiological measurements [28].

In this study, artifact removal was implemented using two distinct strategies, one for the morning and another for the afternoon period. In the morning, rapid changes triggered the exclusion of all measurements from the start of the day up to 15 min after the rise. In the afternoon, rapid changes resulted in the exclusion of measurements from 15 min before the drop until the end of the day. This approach ensured that sudden spikes or drops did not bias the analysis, while also accounting for participants who occasionally arrived after 9:00 a.m. or left before 4:00 pm. A similar approach was used for heart rate, considering artefacts as rapid changes of |50 bpm|.

The |1 °C|-within-1-min threshold was adopted as a conservative criterion for artifact detection, considering that: (i) the procedure was applied separately to morning and afternoon periods, during which no significant thermal transitions occurred (e.g., transitions from outdoor to indoor conditions); (ii) previous studies report an absence of meaningful physiological responses to temperature steps of 4 °C or less [29], and (iii) rapid skin temperature changes are more likely to occur in localized measurements [30,31], rather than in MST as considered here. Since no abrupt indoor thermal changes occurred in the office environment, such rapid skin temperature variations were therefore considered non-physiological and attributed to sensor-related artifacts. Overall, this procedure resulted in the removal of 5.5 % of data points during hotter-than-average days and 3.2 % during cooler-than-average days.

Table 3
Agreement between outdoor temperature classifications (Mean, Max and AT) by season and all year.

	Mean & AT	Mean & Max	Max & AT
Summer	69 %	77 %	77 %
Autumn	93 %	86 %	79 %
Winter	92 %	85 %	77 %
Spring	75 %	92 %	83 %
All year	83 %	85 %	85 %

Linear mixed-effects models were fitted using physiological signals (e.g., skin temperatures and heart rate) as dependent variables and the outdoor thermal scenario ('hotter-than-average' vs. 'cooler-than-average') as the main fixed effect. To account for diurnal trends inherent to dense repeated measurements, time of day was included as a continuous covariate. Participants were included as random intercepts to account for within-subject correlation from repeated measurements, while time-of-day was included to capture systematic temporal structure in the physiological responses.

Two temporal approaches were considered: (i) full-day assessments (9:00 a.m. to 4:00 pm.) and (ii) the lunch-break period only (12:00 pm. to 1:00 pm.). Considering mean skin temperature (MST) as an example, the models were specified *MST* ~ *outdoor thermal scenario* + *time of day* + *(1* + *time of day* | *ID_season)* for the full-day analysis, and as *MST* ~ *outdoor thermal scenario* + *(1* | *ID_season)* for the lunch-break analysis. ID_season represents a grouping factor combining participant identification and season of the year, accounting for participant-specific random intercepts (and random slopes for time of day when included).

Additionally, model diagnostics included inspection of residuals versus fitted values, Q–Q plots of residuals, and the distribution of random effects, indicating no violations of linear mixed-model assumptions. As expected for high-frequency repeated physiological measurements, residual temporal autocorrelation was observed. To evaluate the robustness of the results to temporal dependence, sensitivity analyses were conducted using temporally aggregated data (5-, 15- and 30-min intervals) and alternative random-effects structures. Across these analyses, fixed-effect estimates remained consistent in magnitude and direction, supporting the robustness of the main findings. These aggregated models were used solely for sensitivity checks and not as primary inferential models.

2.4.3. Perceptual responses

A PROBIT regression model, based on the thermal-preference votes, was used to estimate the standard effective temperature at which occupants would report no preference for thermal change. This analysis was conducted for two outdoor scenarios: hotter-than-average and cooler-than-average days. Neutral temperatures were also calculated for both scenarios using two approaches. In the first, thermal sensation votes were treated as responses to the indoor thermal conditions, represented by SET. In the second, an inverse approach was applied, modeling the indoor thermal conditions (i.e., SET) as a response to occupants' thermal sensation, based on current discussions on causal thinking in building science [32].

3. Results

3.1. Outdoor thermal conditions over the seasons and implications for indoor exposure

The climate anomaly observed in Brazil over 2023 was reflected in hotter-than-average mild seasons (i.e., autumn and winter) in the subtropical region assessed. As shown in Fig. 5, both seasons were consistently warmer than historical averages. During autumn, 86 % of the experimental days (12 out of 14) presented outdoor air temperatures above the historical 10-year average (2013–2022). In winter, although a smaller number of days were hotter-than-average, most of them showed substantial increases in outdoor air temperature, exceeding +2 °C on 80 % of those days. A follow-up analysis indicated probabilities of 0.38 and 0.31 for observing outdoor air temperatures at least 2 °C above the historical average during autumn and winter, respectively. These findings highlight the pronounced impact of the 2023 climate anomaly on typically mild seasons.

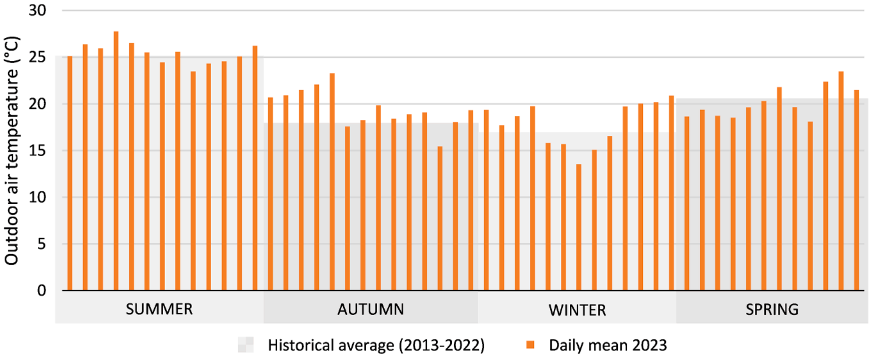

Fig. 5. Characterization of mean outdoor air temperature over the experimental days in comparison with the historical average.

To verify whether the outdoor-based classification translated into distinct indoor thermal exposure, indoor operative temperatures were compared between hotter-than-average and cooler-than-average days across seasons (Table 4). Indoor operative temperatures were higher on hotter-than-average days in autumn, spring, and winter, indicating that the outdoor anomaly was reflected in the indoor thermal context. In summer, indoor operative temperatures remained similar across categories and exhibited reduced variability on hotter-than-average days, consistent with active cooling operation in the mixed-mode office. In the present living lab context, such variations are inherent components of thermal resilience, allowing indoor environments to remain relatively stable despite anomalous outdoor conditions.

3.2. Indoor thermal conditions and subjective responses

Table 4 summarizes the seasonal variability of indoor environmental parameters and user-related factors, distinguishing between days that were cooler-than-average days ($\Delta T < 0$) and hotter-than-average days ($\Delta T > 0$). Operative temperatures were higher on hotter-than-average days in all seasons, except in summer, when occupants relied on mechanical cooling for restoring their thermal comfort levels. Air velocity remained relatively stable across seasons, with lower values observed in summer, when mechanical cooling reduced air movement compared to natural ventilation. Clothing insulation (clo) exhibited strong seasonal variation, ranging from approximately 0.36 clo in summer to 0.97 clo in autumn, reflecting occupants' adaptive behavior. Metabolic rates (met) remained around 1.14 met throughout the year, reflecting the stable activity levels typical of office work.

3.3. Adaptations to the thermal conditions

This subsection shows involuntary and voluntary adaptations (i.e., physiological and behavioral) observed during hotter days, as well as perceptual responses from the participants.

3.3.1. Physiological adaptations

Exposure to hotter outdoor conditions influences both short- and long-term thermoregulatory responses of building occupants. Fig. 6 and Table 5 show mean skin temperature (MST) profiles in the morning, during the lunch break, and in the afternoon throughout the experimental campaign. Mixed-effects modeling indicated that mean skin temperature (MST) was, on average, 0.29 °C higher on hotter-than-average days compared to cooler-than-average ones ($p \approx 0.000$), after accounting for time-of-day effects. A significant diurnal pattern was observed, with MST increasing by approximately 0.12 °C per hour during the monitored daytime period ($p \approx 0.000$). Random intercepts and random slopes for hour revealed substantial inter-individual variability in both baseline MST and diurnal trajectories, reflecting heterogeneous physiological responses under real mixed-mode operating conditions. The largest increases occurred during the lunch break, likely due to direct exposure to the outdoors. When considering only this period, statistical analysis confirmed that MST was, on average, 0.62 °C higher on hotter-than-averager days compared to cooler-than-average ones ($p \approx 0.000$), with individuals exhibiting variability in MST (SD = 0.56 °C) across seasons.

In addition to trends in mean skin temperature across the body, localized temperatures at the hand were assessed to deepen the characterization of thermoregulatory responses throughout the year. Fig. 7 and Table 6 synthesize the results observed over the hotter and cooler days. Hand temperatures (H) were significantly influenced by thermal stimuli during hotter days. Mixed-effects modeling indicated that hand temperature was, on average, 0.88 °C higher on hotter-than-average days compared to cooler-than-average ones ($p \approx 0.000$), after accounting for time-of-day effects. A significant diurnal pattern was observed, with H increasing by approximately 0.19 °C per hour during the monitored daytime period ($p = 0.001$). These results suggest that, similar to MST, localized skin temperature responds physiologically to hotter conditions, showing both inter-individual variability and consistent increases. Additionally, the largest variation was observed during the lunch break, when statistical analysis confirmed that H was 1.55 °C higher on hotter days, with individuals exhibiting variability in MST (SD = 1.41 °C) across seasons.

Finally, potential physiological adaptations to hotter conditions were assessed via participants' heart rate responses. Fig. 8 and Table 7 show the results observed on hotter and cooler days. Mixed-effects model with participant ID as a random intercept to account for inter-individual

Table 4
Variability of indoor parameters throughout the year.

Variables		Summer		Autumn		Winter		Spring	
		$\Delta T < 0$	$\Delta T > 0$	$\Delta T < 0$	$\Delta T > 0$	$\Delta T < 0$	$\Delta T > 0$	$\Delta T < 0$	$\Delta T > 0$
Indoor	To (°C)	26.09 ± 1.13	25.99 ± 0.44	22.89 ± 1.46	25.34 ± 2.00	22.39 ± 1.76	24.41 ± 2.03	23.69 ± 0.72	26.07 ± 0.62
	Air velocity (m/s)	0.03 ± 0.04	0.03 ± 0.02	0.10 ± 0.06	0.12 ± 0.08	0.08 ± 0.04	0.10 ± 0.06	0.08 ± 0.04	0.08 ± 0.05
	RH (%)	66.38 ± 6.50	59.59 ± 4.40	61.35 ± 8.24	63.63 ± 8.55	51.07 ± 7.19	64.66 ± 10.67	67.58 ± 9.36	62.54 ± 5.94
	SET (°C)	24.55 ± 1.69	24.20 ± 1.07	25.82 ± 1.96	25.38± 1.72	23.54± 2.08	25.57 ± 2.24	25.99± 2.07	28.43± 1.77
User-related	clo	0.36 ± 0.08	0.37 ± 0.11	0.97 ± 0.25	0.60 ± 0.18	0.79 ± 0.15	0.67 ± 0.19	0.83 ± 0.23	0.62 ± 0.18
	met	1.15 ± 0.19	1.14 ± 0.19	1.16 ± 0.20	1.13 ± 0.19	1.14 ± 0.19	1.14 ± 0.18	1.15 ± 0.17	1.14 ± 0.17

Mean ± Standard Deviation (SD).

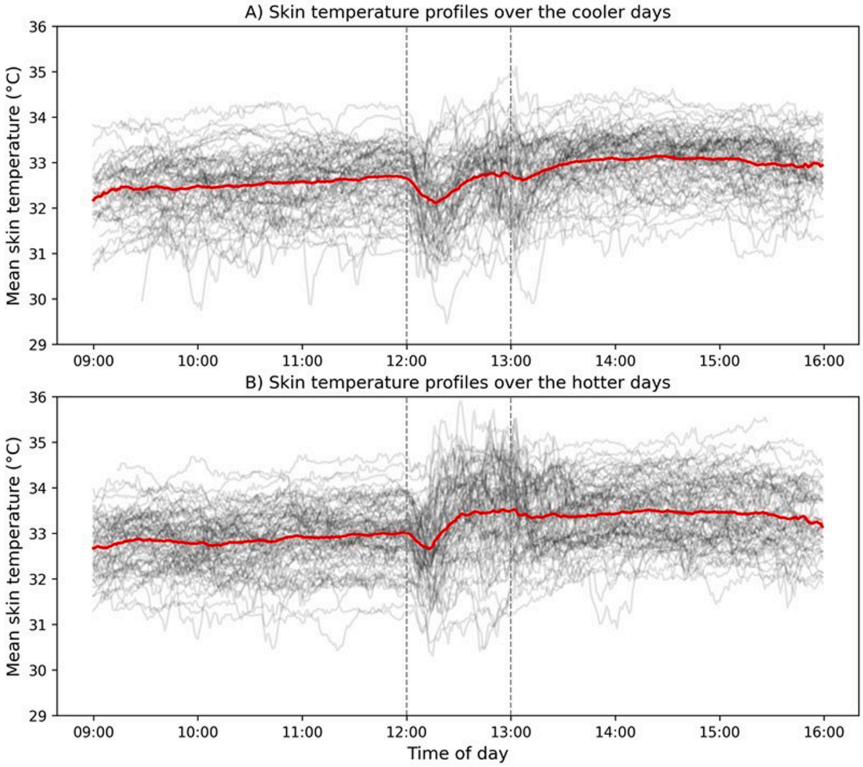

Fig. 6. Mean skin temperatures observed across the year: a) cooler-than-average days, and b) hotter-than-average days.

Table 5
Mean and standard deviations of MST observed during cooler and hotter days in the morning, lunch break, and afternoon.

Period	Cooler days(°C)	Hotter days(°C)
Morning	32.53 ± 0.69	32.86 ± 0.66
Lunch	32.50 ± 0.79	33.21 ± 0.94
Afternoon	32.99 ± 0.65	33.42 ± 0.72

variability indicated that exposure to hotter-than-average conditions had a very small and non-significant effect on heart rate (Δbpm $= 0.08$ bpm; $p = 0.452$), indicating that heart rate remained largely stable under these conditions. Considerable variability was observed between participants (SD $\approx$ 6.99 bpm), reflecting differences in baseline heart rate independent of temperature exposure. Given that heart rate in office environments is strongly influenced by physical activity, posture changes, and psychosocial factors, and that no activity tracking was available in this study, these results should be interpreted as inconclusive with respect to thermal-related physiological responses, rather than as evidence of thermal equivalence or adaptation.

3.3.2. *Behavioral adaptations*

Behavioral responses were tested in terms of both personal and environmental adjustments. In terms of personal responses, clothing insulation adjustments were assessed across seasons. Considering environmental ones, both mechanical ventilation and indoor air velocity adaptation were evaluated.

A wide range of clothing insulation values was observed throughout the year (Fig. 9). As expected, the lowest values occurred in summer, whereas higher values were found in autumn, winter, and spring. Notably, consistent differences were identified between hotter and cooler days. Statistical analysis confirmed that these differences were significant across all seasons (Summer: −0.04 clo, $p = 0.000$; Autumn: −0.26 clo, $p = 0.000$; Winter: −0.11 clo, $p = 0.000$; Spring: −0.27 clo, $p = 0.000$).

In addition to personal adjustments of clothing values, indoor air velocities were assessed as an index for adjustments of building systems and interfaces during hotter conditions caused by climate anomalies. Fig. 10 highlights continuous monitoring of omnidirectional air velocity near the experiment participants. Statistical analysis indicated a significant effect of outdoor thermal conditions on indoor air velocity (0.03; $p < 0.001$), supporting the observation that higher indoor air velocities were consistently noted on hotter-than-average days.

HVAC usage follows a clear seasonal pattern (Fig. 11). In summer and winter, it remains fairly consistent (summer: ON, winter: OFF) and is less influenced by daily temperature changes. In transitional seasons, hotter days lead to increased usage, which is more influenced by outdoor temperature variations.

3.3.3. *Perceptual responses*

Fig. 12 shows the distribution of indoor SET across seasons, distinguishing cooler ($\Delta T < 0$) and hotter ($\Delta T > 0$) days. SET was used sequentially to determine the preferred standard effective temperatures for daily conditions. Fig. 13 shows these preferred standard effective temperatures. Results indicated a reduction of about 1 °C in indoor SET on hotter days: from 25.75 °C to 24.79 °C.

The distribution of thermal preference scores was non-normal in both groups (Shapiro–Wilk $p < 0.001$). Therefore, a non-parametric Mann–Whitney U test was conducted, which indicated that thermal preference differed significantly between hotter-than-average and cooler-than-average days ($U = 365{,}220.5$, $p < 0.001$).

Neutral temperatures were calculated considering the differences between hotter-than-average and cooler-than-average days. Fig. 14 shows the standard effective temperature (SET) considered thermally neutral, using the classic approach of treating occupants' thermal sensations as a response to indoor temperatures. In such a case, a reduction of 1.12 °C on SET was observed on hotter-than-average days (25.18 °C) compared to those similar or cooler-than-average (26.30 °C). Alternatively, Fig. 15 presents an approach that considers indoor thermal conditions as a response to occupants' thermal sensations. In this case, a

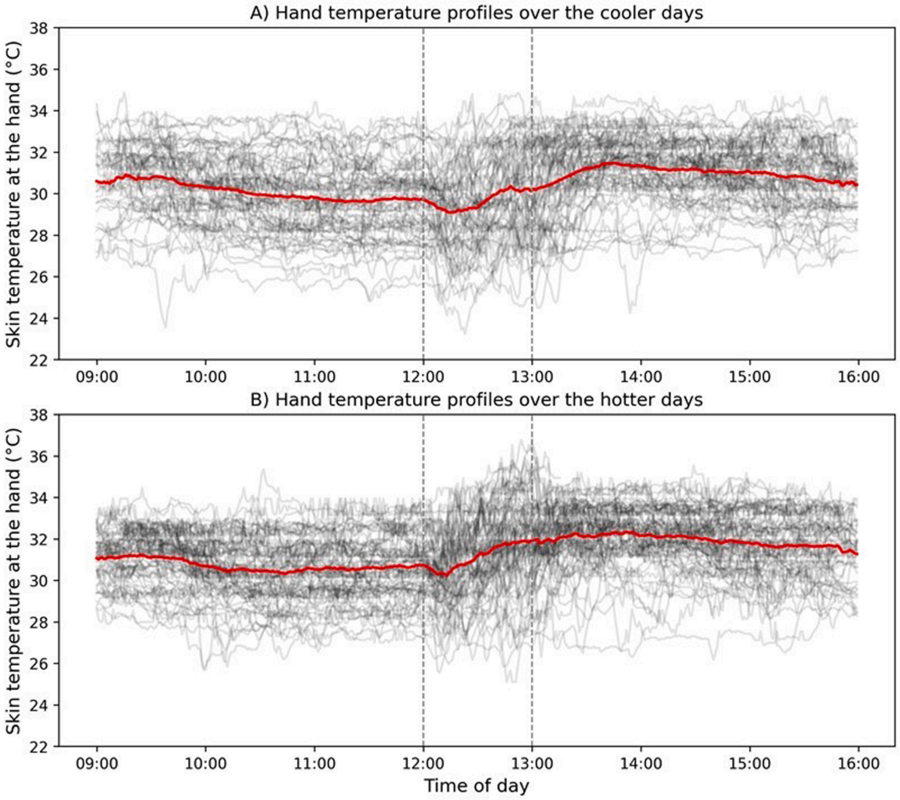

Fig. 7. Hand temperatures observed across the year: a) cooler-than-average days, and b) hotter-than-average days.

Table 6
Mean and standard deviations of hand temperature observed during cooler and hotter days in the morning, lunch break and afternoon.

Period	Cooler days(°C)	Hotter days(°C)
Morning	30.07 ± 1.79	30.70 ± 1.51
Lunch	29.66 ± 2.08	31.15 ± 1.98
Afternoon	30.98 ± 1.65	31.95 ± 1.54

minor shift in the neutral SET of +0.12 °C was observed when comparing both scenarios (from 25.25 °C to 25.37 °C).

4. Discussions

The scientific literature largely reports the potential of mixed-mode buildings to provide indoor thermal comfort to occupants, aligned with core aspects of the adaptive theory [9,33]. However, the impact of climate anomalies on indoor thermal comfort remains unclear, and real-world measurements of physiological responses to environmental triggers in mixed-mode buildings are limited. This section discusses our results in the context of the previous literature, considering distinct outcomes observed during hotter-than-average days in a year influenced by the El Niño effects in South America, resulting in anomalous climate conditions. In this study, adaptive resilience is assessed through occupants' physiological, behavioral, and perceptual adjustments in response to anomalous outdoor conditions, acknowledging that indoor environments in mixed-mode buildings are not expected to directly mirror outdoor forcing.

4.1. Physiological adaptations

The longitudinal monitoring during 2023 provided evidence of physiological adjustments in response to hotter-than-average outdoor conditions. The statistically significant increase in mean skin temperature (MST) and hand temperature on hotter days quantified the involuntary thermoregulatory response to the warmer exposure. Along these lines, a compelling finding was the largest increase in both MST and hand temperatures, especially during the lunch break period (from 11:00 to 12:00), likely reflecting outdoor exposures by the participants. Previous studies have shown that employees' autonomy [34] and walking in nearby parks [35] during lunch breaks are positively associated with overall well-being. From an environmental perspective, outdoor-to-indoor spatial and thermal transitions are reflected in substantial psychophysiological responses [36]. Considering the potential benefits of outdoor exposure over a working day, alongside the current climate emergency and its potential harms from extreme events, building occupants must have options to improve and restore their comfort levels.

Although the present study did not assess the potential of localized air movements caused by Personalized Environmental Control Systems (PECS), previous research also highlighted their impacts. Both desk fans and small evaporative coolers significantly affected near-body air temperature and relative humidity, and reduced occupants' MST during outdoor-to-indoor transitions [37]. The current findings further complement this discussion, as low-energy solutions, such as desk fans, are feasible ways to support occupants in adapting to the effects of climate anomalies on indoor thermal experiences and perceptions, instead of relying on energy-intensive solutions.

In contrast, the non-significant change in heart rate may suggest that the thermoregulatory response was primarily mediated by skin temperature adjustments and behavioral responses, indicating that the heat exposure was not severe enough to induce significant cardiovascular strain in this mixed-mode office setting. Along these lines, the behavioral adaptations comprising clothing adjustments and higher air velocities enable heat dissipation through the occupants' skin, keeping physiological stress manageable. In future studies, more advanced equipment can be implemented to assess potential variations in cardiovascular responses to hotter-than-average conditions [38], as the

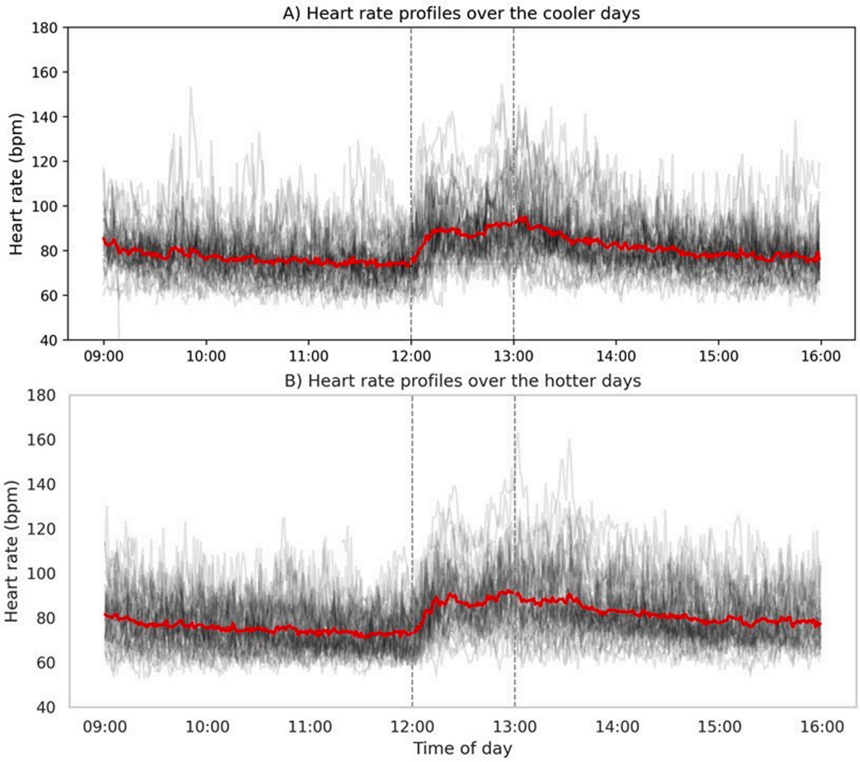

Fig. 8. Heart rates observed across the year: a) cooler-than-average days, and b) hotter-than-average days.

Table 7
Heart rates observed during cooler and hotter days in the morning, lunch break and afternoon.

Period	Cooler days (bpm)	Hotter days (bpm)
Morning	76.48 ± 10.46	75.21 ± 10.29
Lunch	87.53 ± 14.14	86.09 ± 13.97
Afternoon	81.51 ± 11.91	81.85 ± 12.55

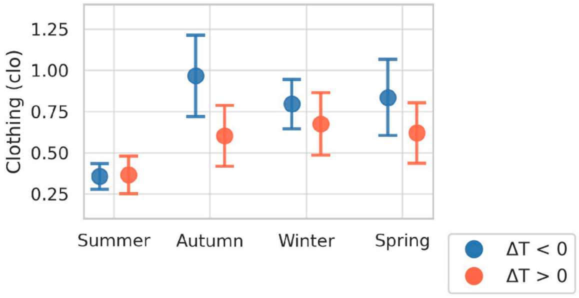

Fig. 9. Clothing values observed in each season.

literature suggests that heart rates may be biased in accurately monitoring physiological responses to thermal exposures.

4.2. Behavioral adaptations

This study demonstrated that behavioral adaptations are critical for coping with climate anomalies in mixed-mode buildings. Our results show that on hotter-than-average days, occupants combine lower clothing insulation levels with higher indoor air velocities. The observed large variability in clothing insulation across seasons, rather than reliance on fixed seasonal values, aligns with previous studies [14,15] conducted in the same city during climatically typical years, suggesting that adaptive clothing behavior remains consistent even under anomalous climatic conditions. Statistical analyses confirmed significant differences in clothing insulation between hotter-than-average and cooler-than-average days within the same season, reinforcing this point.

Previous studies in mixed-mode buildings during non-anomalous years have shown that some coping patterns (such as switching to air conditioning, with potential risks of overcooling) are not exclusive to climate anomalies but are characteristic of mixed-mode operation when occupants have access to control [18]. These studies also suggest that air velocity does not always directly affect thermal sensation under natural ventilation mode [39], but it can indirectly influence comfort through perceived air movement. Nonetheless, the increase in indoor air velocities observed in our study suggests adaptation strategies during hotter periods, particularly under anomalous climatic conditions. These findings are consistent with adaptive comfort theory, which highlights the role of personal control in supporting thermal comfort [40]. By providing occupants with sufficient control over both their environment and dress code, adaptive behaviors emerge as key mechanisms for coping with temperature variations, including that arising from anomalous climatic conditions.

While this study focused on clothing and air movement, other low-cost strategies, including consuming cold beverages [16] or using personalized environmental control systems [41,42], likely complement these behaviors. Typically, thermal comfort ranges are reported for clothing insulation of 0.5 and 1.0 clo for summer and winter, respectively [26]. However, under the influence of climate anomalies, higher average clothing insulation was observed in milder seasons (spring and autumn) compared to winter. This highlights the importance of providing occupants with autonomy to adjust clothing, rather than enforcing fixed dress codes [43,44], as a practical and low-cost approach to enhance resilience to thermal stress.

Interface design and building features may support adaptive behaviors by shaping the potential for occupant interaction with environmental controls. A literature review highlighted the impact of interface design on the optimization of occupant behaviors [45],

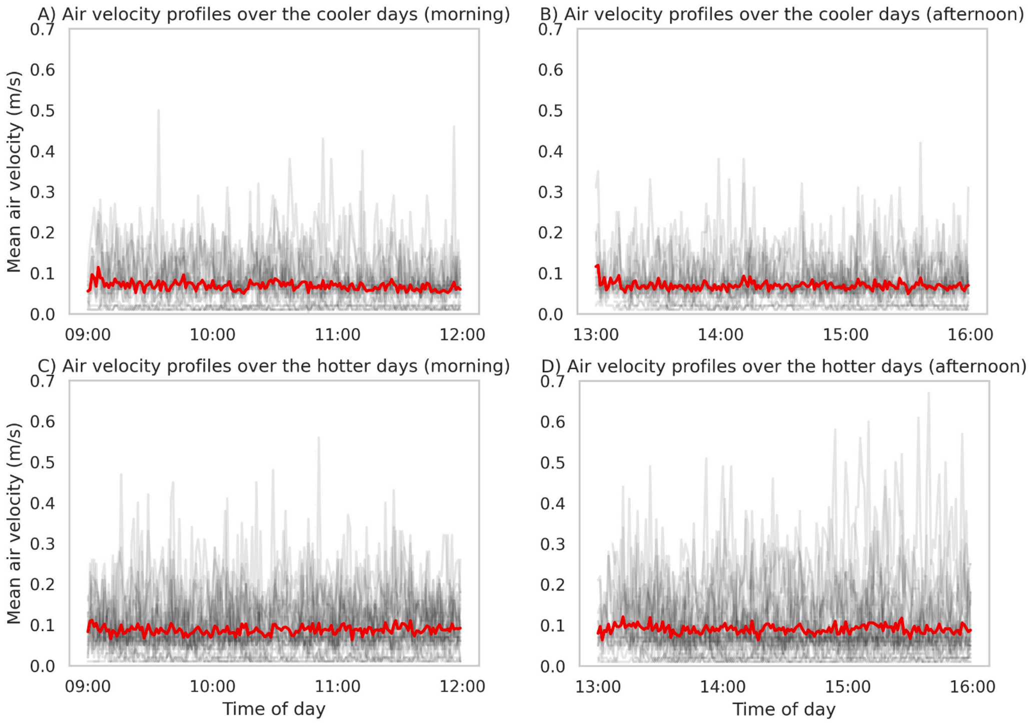

Fig. 10. Indoor air velocities measured over the year: a) cooler-than-average days (morning), b) cooler-than-average days (afternoon), c) hotter-than-average days (morning), and d) hotter-than-average days (afternoon).

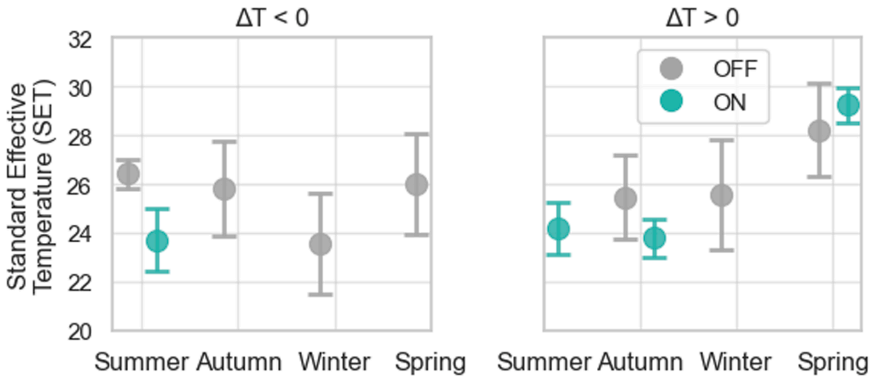

Fig. 11. Seasonal SET by HVAC Use (cooler-than-average days and hotter-than-average days).

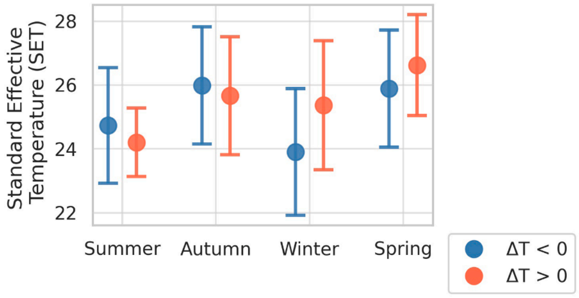

Fig. 12. Indoor SET distribution across the seasons.

emphasizing that accessibility, ease of operation, and flexibility can influence occupants' likelihood of adjusting windows and other building systems. In the facility studied, operable windows are available on opposite façades, which provides architectural conditions favorable to cross-ventilation and enhanced natural ventilation potential [46,47]. Within this architectural configuration, the indoor air-velocity levels and temporal variability observed during monitoring are consistent with airflow patterns reported in naturally ventilated environments in the literature [48]. These results are interpreted as reflecting the ventilation potential afforded by the building design, instead of providing evidence of specific occupant actions, since window state and PECS use were not objectively logged in this study.

4.3. *Perceptual responses*

A core finding of this study is the statistically significant shift in occupants' thermal preferences when comparing hotter-than-average and cooler-than-average days. The PROBIT analysis showed that the preferred SET was approximately 1 °C lower on hotter days (24.79 °C) than on cooler days (25.75 °C). At first glance, this result appears counter-intuitive in light of adaptive comfort theory, which posits that exposure to warmer outdoor conditions increases the preferred indoor temperature setpoint [49]. However, the observed inclination toward cooler conditions during already hot days can be interpreted within the

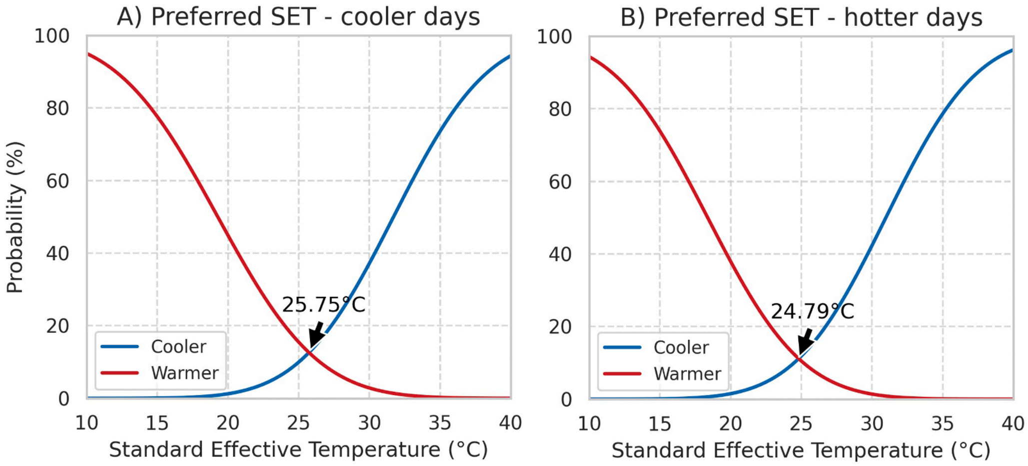

Fig. 13. Preferred standard effective temperatures considering: a) cooler-than-average days, and b) Hotter-than-average days.

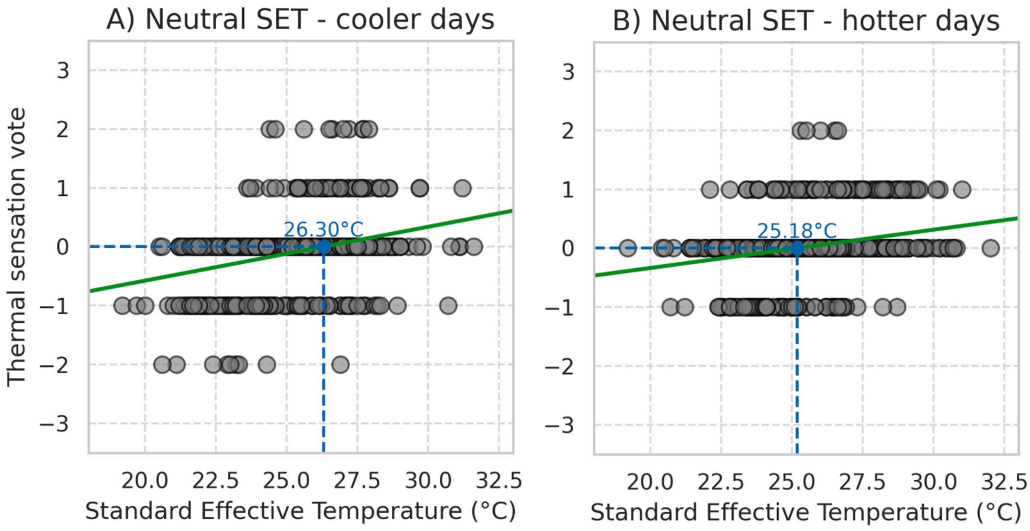

Fig. 14. Neutral temperatures considering occupants' thermal sensation as a response to indoor temperatures during: a) cooler-than-average days, and b) Hotter-than-average days.

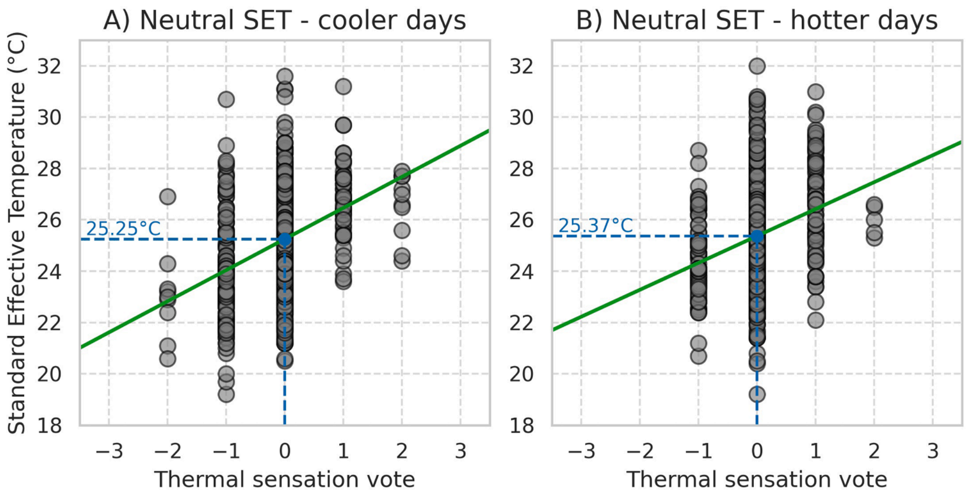

Fig. 15. Neutral temperatures considering indoor temperatures as a response to occupants' thermal sensations during: a) cooler-than-average days, and b) Hotter-than-average days.

mixed-mode (MM) context and through the lens of alliesthesia. In the MM context, although the literature suggests that HVAC should be the last resort when restoring thermal comfort [9], the availability of mechanical cooling may trigger an instantaneous preference for relief from heat. Indeed, our results confirmed that, besides summer, HVAC was only used in mild seasons (autumn and spring) on hotter-than-average days. This aligns with previous work documenting expectations for cooler indoor environments in hot regions [50,51] and evidence that thermal "no-change" preference votes are often associated with "slightly cool" thermal sensations [52].

More critical insights, however, arise from the divergence observed between the two approaches used to estimate neutral SET on hotter-than-average versus cooler-than-average days. This discrepancy aligns with recent discussions about assumptions and interpretations related to statistical modelling in building-science research [32,53]. When applying classic formulations that treat thermal sensation as a response to SET (TS ← SET), neutral SET was 1.12 °C lower on hotter days, likely reflecting stronger alliesthesial demand for cooling and aligning with previously reported preferred temperatures. In contrast, when modeling indoor thermal conditions as a response to occupants' thermal sensation (SET ← TS), the difference in neutral SET is $+0.12$ °C. The s approach models the temperature that occupants aim to achieve when they intervene via behavioral adaptations (e.g., adjustments to personal or environmental control opportunities), as typically described in mixed-mode settings.

Taken together, these findings suggest that the ways in which building scientists model and interpret statistical analyses of occupants' thermal perceptions may shape the inferred impacts of climate anomalies. Analyses that implicitly assume stable indoor conditions may bias interpretations toward cooler indoor targets or more conservative thermal control assumptions, whereas occupant-centric, adaptive formulations reveal greater stability in preferred temperatures. Understanding which perspective is appropriate is therefore critical when interpreting thermal-comfort dynamics in mixed-mode buildings under climatic variability.

5. Limitations and future studies

Several limitations of this study should be acknowledged. First, although the living lab provides access to Personalized Environmental Control Systems (PECS), such as small desk fans, their actual use was not monitored. These devices may have contributed to reducing physiological strain on warmer days and potentially moderated reliance on HVAC. Future studies should integrate objective monitoring of PECS usage to better capture their contribution to adaptive behaviors.

Participants' lunchtime activities were not controlled, and the protocol did not provide information about periods spent outside the office during lunch. Consequently, physiological responses measured around lunchtime may have been influenced by uncontrolled factors such as food intake, metabolic activation, short-term outdoor exposure, or activity patterns. As a consequence, this period represents a potential confounding influence. However, the study was designed as a living lab, aiming to capture occupants' natural interactions with the building according to their daily schedules. Repeated measurements across multiple days and seasons for each participant, together with the inclusion of participant IDs in all statistical models, likely helped distribute individual lunch-related effects. Standardizing, or at least documenting, lunchtime exposure would strengthen future studies examining the influence of outdoor climate on subsequent indoor comfort responses.

Indoor measurements were taken in close proximity to a maximum of four occupants seated at adjacent workstations arranged in a compact cluster; however, point-based sensing cannot fully capture individual thermal exposure, especially for air velocity and radiant temperature variations at the personal scale. The results therefore reflect shared near-field thermal conditions among adjacent occupants rather than individualized microclimate exposure, particularly due to the logistics of installing a full set of sensors for each participant.

The classification of experimental days as hotter- or cooler-than-average was unevenly distributed across seasons, with some seasons predominantly represented by a single thermal category. This imbalance may partially confound thermal category effects. Consequently, the results should be interpreted as year-long, within-season contrasts under anomalous climatic conditions rather than as fully season-independent effects. Although the overall number of responses was balanced across thermal categories at the annual scale, season-specific sub-analyses were not always feasible due to sample size constraints.

Although the sample size was modest relative to typical field studies and the gender distribution was unbalanced (12 women and 9 men), the experiment involved semi-controlled conditions and continuous physiological monitoring, which limits feasible participant numbers. Importantly, each participant completed at least two experimental rounds per season, improving statistical power through a within-subject design. Future studies could scale up sample sizes by incorporating less invasive physiological monitoring technologies or by combining multi-site living labs.

6. Conclusion

This study examined how occupants of a mixed-mode office building adapted physiologically, behaviorally, and perceptually to anomalous climatic conditions observed in 2023 in South America, which produced unusually warm conditions during typically mild seasons in a subtropical climate.

The results show that hotter-than-average days triggered consistent thermoregulatory responses, including elevated mean and localized skin temperatures. Occupants also engaged in behavioral adjustments during hotter days, such as reducing clothing insulation. These periods also coincided with higher recorded indoor air velocities, which are consistent with increased air movement and enhanced heat dissipation.

Perceptual responses revealed a significant shift toward cooler thermal preferences on hotter days. However, the magnitude of this shift depended strongly on how thermal perceptions were conceptualized and modeled. When thermal sensation was treated as the response variable to indoor thermal conditions, the analysis indicated a reduction in neutral SET of -1.12 °C, suggesting higher cooling requirements. In contrast, when indoor thermal conditions were treated as the response to occupants' thermal sensation, the estimated shift was minimal ($+0.12$ °C). This divergence highlights that analytical assumptions can alter conclusions about cooling needs during climate anomalies.

Taken together, the findings indicate that mixed-mode buildings can maintain thermal comfort under climatic variability when occupants are provided with meaningful control opportunities. Adaptive comfort strategies, including personal and environmental adjustments (e.g., changes in clothing levels and measured air velocities), may support adaptive capacity by enabling occupants to respond to warmer conditions without necessarily relying on HVAC operation. The synergy between the coping strategies observed further supports adaptive capacity at both the occupant and building levels under the effects of climate anomalies. As climate anomalies become more frequent, incorporating adaptive comfort principles into design and operation will be essential to avoid unnecessary energy use while safeguarding occupants' comfort and well-being.

CRediT authorship contribution statement

Mateus Bavaresco: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Brenda da Costa Loeser:** Writing – original draft, Visualization, Validation, Investigation, Data curation, Conceptualization. **Liége Garlet:** Writing – original draft, Visualization, Investigation, Data curation. **Natasha Hansen Gapski:** Writing – original draft, Visualization, Investigation, Data curation. **Ana Paula Melo:** Writing – review & editing, Supervision, Funding acquisition. **Roberto Lamberts:** Writing – review & editing, Supervision,

Funding acquisition.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Appendix A. Full questionnaire

Table A1

Table A1
Questions and answer options included in the full questionnaire.

Question	Answer option
Anthropometric and behavioral patterns	
1.1 Age	Integer value / Prefer not to answer
1.2 Gender	Male / Female / Prefer not to answer
1.3 Highest education level	Elementary / High school / Undergraduate / Master’s / Doctorate / None / Prefer not to answer
1.4 Height	Numeric value / Prefer not to answer
wt	Numeric value / Prefer not to answer
1.6 Length of residence in the city	< 1 year / 1–3 years / > 3 years / Prefer not to answer
1.7 Upper-body clothing	Sleeveless / Tank top / Short-sleeve shirt / T-shirt / Short-sleeve formal shirt / Long-sleeve formal shirt / Sweater / Light jacket / Vest / Prefer not to answer
1.8 Lower-body clothing	Thin trousers / Thick trousers / Shorts / Bermuda / Short skirt / Long skirt / Prefer not to answer
1.9 One-piece clothing	Long dress / Short dress / Overalls / Jumpsuit / Prefer not to answer
1.10 Footwear	Tights / Ankle socks / Mid-length socks / Long socks / Boots / Shoes or sneakers / Flats / Sandals or flip-flops / Prefer not to answer
1.11 Sleep quality (last week)	1 (worst) – 5 (best)
1.12 Stress level (last week)	1 (worst) – 5 (best)
1.13 Eating habits (last week)	1 (uncommon) – 5 (common)
1.14 Physical activity habits (last week	1 (uncommon) – 5 (common)
2. Sensitivity	
2.1 Sensitivity to cold climate	1 (low) – 5 (high)
2.2 Sensitivity to hot climate	1 (low) – 5 (high)
2.3 Sensitivity to low air movement	1 (low) – 5 (high)
3. Thermal Perception and Comfort	
3.1 Left the room in last 30 min	Yes / No
3.2 Time spent outside the room	0–5 min / 5–10 min / 10–15 min / > 15 min
3.3 Perception of visited environment	Type, thermal perception, ventilation type, air velocity, and solar exposure of the visited environment
3.4 Predominant activity (last 30 min)	Sitting (rest/reading) / Sitting (typing) / Standing (relaxed) / Standing (walking same space) / Standing (walking other space)
3.5 Caffeine intake (last 30 min)	Yes / No
3.6 Meal intake (last 30 min)	Yes / No
3.7 Clothing added (last 30 min)	Open-ended
3.8 Clothing removed (last 30 min)	Open-ended
3.9 Overall thermal sensation	Cold / Cool / Slightly cool / Neutral / Slightly warm / Warm / Hot
3.10 Thermal comfort evaluation	Comfortable / Slightly uncomfortable / Uncomfortable / Very uncomfortable / Extremely uncomfortable
3.11 Thermal preference	Much cooler / Cooler / Slightly cooler / No change / Slightly warmer / Warmer / Much warmer
3.12 Hand thermal sensation	Cold / Cool / Slightly cool / Neutral / Slightly warm / Warm / Hot
3.13 Trunk thermal sensation	Cold / Cool / Slightly cool / Neutral / Slightly warm / Warm / Hot
3.14 Feet thermal sensation	Cold / Cool / Slightly cool / Neutral / Slightly warm / Warm / Hot
3.15 Thermal acceptability	Clearly acceptable / Just acceptable / Just unacceptable / Clearly unacceptable

Data availability

Data will be made available on request.

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