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Indoor Thermal Comfort During Warmer-than-Usual Autumn and Winter Conditions in a Mixed-Mode Office

Conforto térmico durante outono e inverno mais quentes que o habitual em um escritório de ventilação mista

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Resumo

Este estudo investiga as respostas fisiológicas, comportamentais e perceptivas de ocupantes em um escritório em Florianópolis, Brasil, durante dias de outono e inverno mais quentes que a média histórica. Um experimento com 21 participantes combinou o monitoramento contínuo da temperatura da pele em dez regiões do corpo e de variáveis ambientais com questionários sobre percepção térmica e vestimenta. Os resultados indicam respostas ao calor, com aumento da temperatura média da pele e das temperaturas das mãos, especialmente após o almoço. Os ocupantes também reduziram o isolamento térmico das roupas e aumentaram o movimento do ar como estratégias adaptativas. Apesar das condições mais quentes que o usual, o conforto térmico foi mantido quando havia oportunidades de adaptação. Os resultados indicam que escritórios de modo misto podem acomodar anomalias térmicas de curto prazo por meio da combinação entre respostas fisiológicas e ações adaptativas dos ocupantes.

Palavras-chave: Mudanças climáticas. Conforto térmico. Operação centrada nos usuários. Adaptação térmica.

Abstract

This study investigates the physiological, behavioral, and perceptual responses of occupants in an office in Florianópolis, Brazil, during autumn and winter days that were warmer than the historical average. An experiment involving 21 participants combined continuous monitoring of skin temperature at ten body sites and environmental variables with questionnaires to assess thermal perception and clothing. The results indicate responses to heat, including increases in mean skin temperature and hand temperatures, particularly after lunch. Occupants also reduced clothing insulation and increased air movement as adaptive strategies. Despite warmer-than-usual conditions, thermal comfort was maintained when adaptive opportunities were available. Overall, the findings indicate that mixed-mode offices can accommodate short-term thermal anomalies through a combination of physiological responses and occupants' adaptive actions.

Keywords: Climate change. Thermal comfort. Human-centric operation. Thermal adaptation.

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INTRODUCTION

Extreme climate anomalies pose challenges for indoor environmental quality, particularly in buildings that rely on adaptive interactions between occupants and their environment to maintain acceptable comfort conditions. El Niño events intensify temperature and precipitation extremes across South America [1], creating atypical seasonal conditions that may expose building occupants to prolonged and unexpected thermal stress. El Niño conditions that developed during the second half of 2023 and persisted into early 2024 have been associated with above-average temperatures and extreme rainfall across southern Brazil [2,3]. While the broader climatic impacts of El Niño are well documented, empirical evidence addressing how such climatic anomalies translate into indoor thermal conditions and influence human thermal comfort and adaptation remains limited.

Adaptive thermal comfort theory emphasizes the role of physiological acclimatization and behavioral adjustments in mediating comfort under variable environmental conditions [4]. However, most field evidence underpinning adaptive models derives from climatically regular periods, potentially underrepresenting responses during extreme or anomalous years [5]. This limitation is particularly relevant for mixed-mode buildings, where indoor conditions remain strongly coupled to outdoor climate and where occupants actively engage with adaptive opportunities such as window operation, clothing adjustment, and ventilation control [6]. Under anomalous climatic exposure, these adaptive mechanisms may be intensified, constrained, or reconfigured in ways that are not fully captured by existing comfort frameworks.

Living laboratories offer a valuable framework to investigate these dynamics under real-world conditions [7], preserving everyday patterns of use and occupant control while capturing seasonal variability and extreme events. The conceptual difference between living labs and climate chambers position such infrastructures as a potential mean to assess thermal comfort trends under the exposure to climate anomalies [7,8]. In mixed-mode contexts, this approach enables observation of how occupants respond to intensified thermal exposure through both involuntary physiological processes and deliberate behavioral strategies. Therefore, evaluating occupants' response throughout sustained climate anomalies in mixed-mode living laboratories may contribute innovative knowledge to the field of adaptive thermal comfort.

This study addresses this gap by examining human psychophysiological responses to indoor environments over a year dominated by a climatic anomaly. The research was conducted in a mixed-mode living laboratory, i.e., an instrumented office where occupants perform their daily activities while indoor conditions and occupant responses can be continuously monitored [7], in Florianópolis, southern Brazil, during the period affected by El Niño. The present study is focused on the autumn and winter periods, when hotter-than-expected conditions shifted the usual seasonality patterns typically observed in the city. Physiological responses, including skin temperatures measured at multiple body locations, and behavioral adaptations, such as clothing insulation, were monitored alongside subjective thermal perceptions during full-day

experimental sessions. By documenting adaptive responses under warmer-than-usual seasonal conditions, this work contributes empirical evidence to ongoing discussions on thermal comfort resilience, occupant adaptability, and the performance of mixed-mode buildings in a changing climate.

METHODS

This paper builds on a broader full-year monitoring campaign conducted in a mixed-mode office building, focusing here on autumn and winter conditions, when warmer-than-average outdoor temperatures were most frequent.

EXPERIMENTAL PROTOCOL

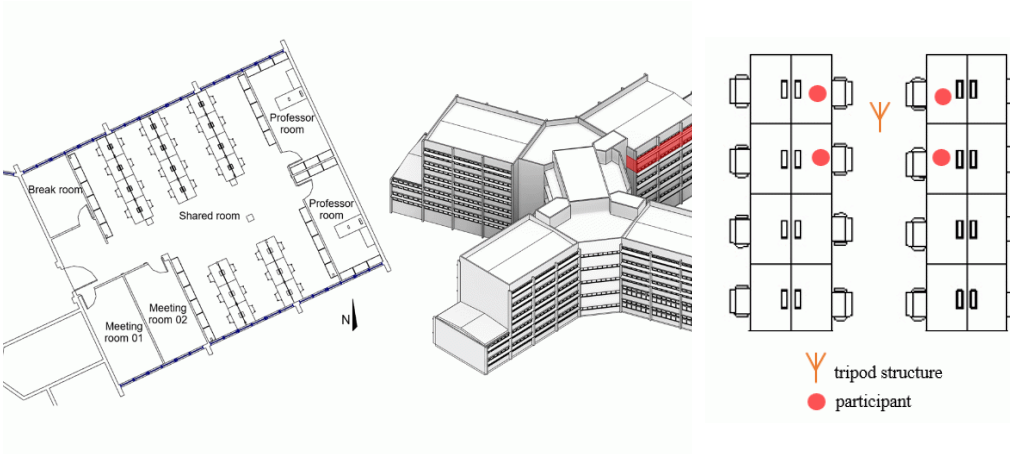
The study was conducted in a living lab office environment at the Federal University of Santa Catarina (UFSC), located in Florianópolis, southern Brazil. The monitored space consists of an open-plan office (shown in Figure 1-a) where occupants perform typical office activities and have access to operable windows and air-conditioning units. During the experiments, participants were allowed to freely adjust their environment, including window operation and clothing choices.

Participants were undergraduate and graduate students who routinely used the office as their regular workplace. During the monitoring sessions, they performed their usual academic activities, including computer work, reading, writing, and meetings, while following their normal daily routine. Short interruptions, such as visits to the restroom or pantry, were permitted. Each participant took part in at least two experimental days per season, and the same cohort was monitored throughout the study. Lighting conditions were not experimentally controlled. Occupants were free to operate blinds and electric lighting according to their usual preferences in order to preserve realistic working conditions.

Monitoring was carried out during regular working hours, from 09:00 to 12:00 and from 13:30 to 16:00. Participants followed their usual eating and drinking habits. Lunch was taken during the scheduled break (12:00–13:30), while water and coffee consumption were unrestricted. Participants were instructed to avoid alcohol before the experimental day and vigorous physical exercise during the previous 24 h. Environmental measurements and subjective surveys were collected at 30-minute intervals. Measurements were conducted nearby occupants (Figure 1-b), considering a maximum of four participants per experimental session. Although data were collected throughout the year, the present analysis focuses exclusively on autumn and winter, when outdoor temperatures most frequently exceeded historical seasonal averages.

Figure 1: Living lab characterization considering: a) the building and its indoor layout, and b) indoor disposition of the equipment for a cluster of participants.

a) b)



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PARTICIPANTS AND MEASURED VARIABLES

A total of 21 participants took part in the study, with repeated participation across multiple experimental days. Among them, 12 were female and 9 were male, with mean ages of 32 ± 8 and 29 ± 3 years, respectively.

Physiological responses were assessed through continuous skin temperature monitoring using Thermochron iButton sensors (resolution 0.0625 °C) at 60-second intervals. Sensors were placed on ten locations of each participant's body, following the method 10c presented by [9]. Mean skin temperature (MST) was calculated based on all the body locations using the equation presented by [9], and localized hand temperatures were analyzed separately to capture peripheral thermoregulatory responses.

Behavioral adaptations were evaluated through self-reported clothing ensembles, which were converted into total clothing insulation values (clo) using standardized insulation coefficients presented by [10]. Indoor thermal conditions necessary to calculate Standard Effective Temperatures (SET) were measured near participants' workstations. These measurements included air temperature, relative humidity, globe temperature, and air velocities. A maximum of four participants, seated on nearby workstations, attended each experimental round to guarantee that indoor conditions are representative for each of them. Indoor air velocity was used as a proxy for adaptive ventilation actions, such as window operations.

Thermal perceptions were obtained from repeated questionnaires (every 30 minutes) using ASHRAE-type scales [10]. In this study, thermal sensations, measured in a seven-point scale was used to estimate neutral temperatures.

CLASSIFICATION OF OUTDOOR CONDITIONS AND DATA ANALYSIS

To examine the influence of thermal anomalies, experimental days were classified as hotter-than-average or cooler-than-average based on daily mean outdoor air temperatures. A 10-year historical dataset (2013–2022) was used to establish seasonal baseline temperatures for the corresponding calendar periods. Days with mean temperatures exceeding the historical average were classified as hotter-than-average, while days with smaller mean temperatures were classified as cooler-than-average. Further analyses included comparisons among physiological, behavioral and perceptual adaptations considering both groups of climate conditions.

Linear mixed-effects models were fitted using physiological (e.g., skin temperatures) or environmental signals (e.g., air velocity) as dependent variables and the outdoor thermal scenario (‘hotter-than-average’ vs. ‘cooler-than-average’) as the fixed effect. Participants were included as random intercepts to account for repeated measurements. Neutral temperatures were calculated using two alternative analytical assumptions: (i) modeling thermal sensation as a function of indoor thermal conditions, and (ii) modeling indoor thermal conditions as a function of occupants' thermal sensation, thereby representing two complementary analytical perspectives for estimating neutral temperatures. Thermal sensation was obtained from the participants' questionnaire responses.

RESULTS AND DISCUSSIONS

Outdoor air temperatures exceeded the historical 10-year seasonal means in 85% of autumn days and 59% of winter days, confirming the sustained influence of the El Niño anomaly on local climate. Although largely known for its influence on rainfall patterns in Southern America [11], El Niño anomalies are also associated with higher likelihoods of positive temperature anomalies. The following subsections present and discuss the consequences in terms of physiological, behavioral and perceptual adaptations by the participants of this study.

PHYSIOLOGICAL ADAPTATIONS

Physiological indicators revealed clear heat-related responses during autumn and winter, with higher localized and mean skin temperatures on hotter-than-average days compared to regular ones. Figure 2 presents mean skin temperature (MST) across the monitoring period, grouped by outdoor thermal conditions. Statistical models showed that MST increased by 0.33 °C on hotter days ($p < 0.001$).

Localized responses were even more pronounced. As shown in Figure 3, hand temperatures increased by 1.17 °C on hotter days compared to regular days ($p < 0.001$), indicating intensified peripheral thermoregulatory activity under warmer exposure. These changes quantify involuntary physiological responses to short-term thermal anomalies, even during seasons typically characterized by milder conditions.

The strongest responses were observed during the lunch break period. During this interval, MST increased by 0.47 °C and hand temperature by 1.74 °C on hotter days

relative to cooler days ($p < 0.001$ for both). Although outdoor exposure was not controlled during lunch breaks, the magnitude and timing of these responses suggest a strong influence of outdoor thermal conditions prior to re-entering the indoor environment, consistent previous studies highlighting the influence of outdoor-to-indoor transitions on human responses [12].

Figure 2: Mean skin temperatures measured during autumn and winter.

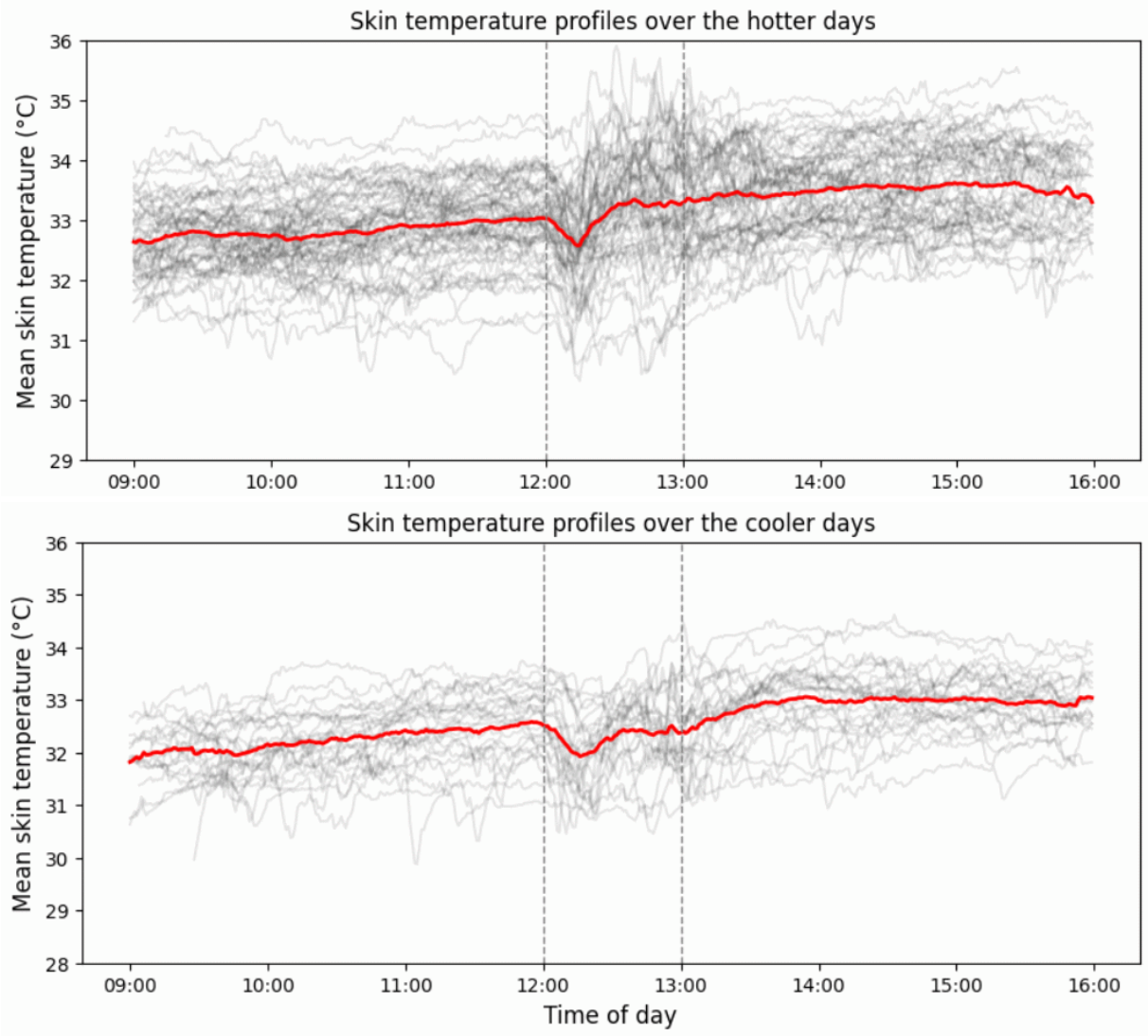

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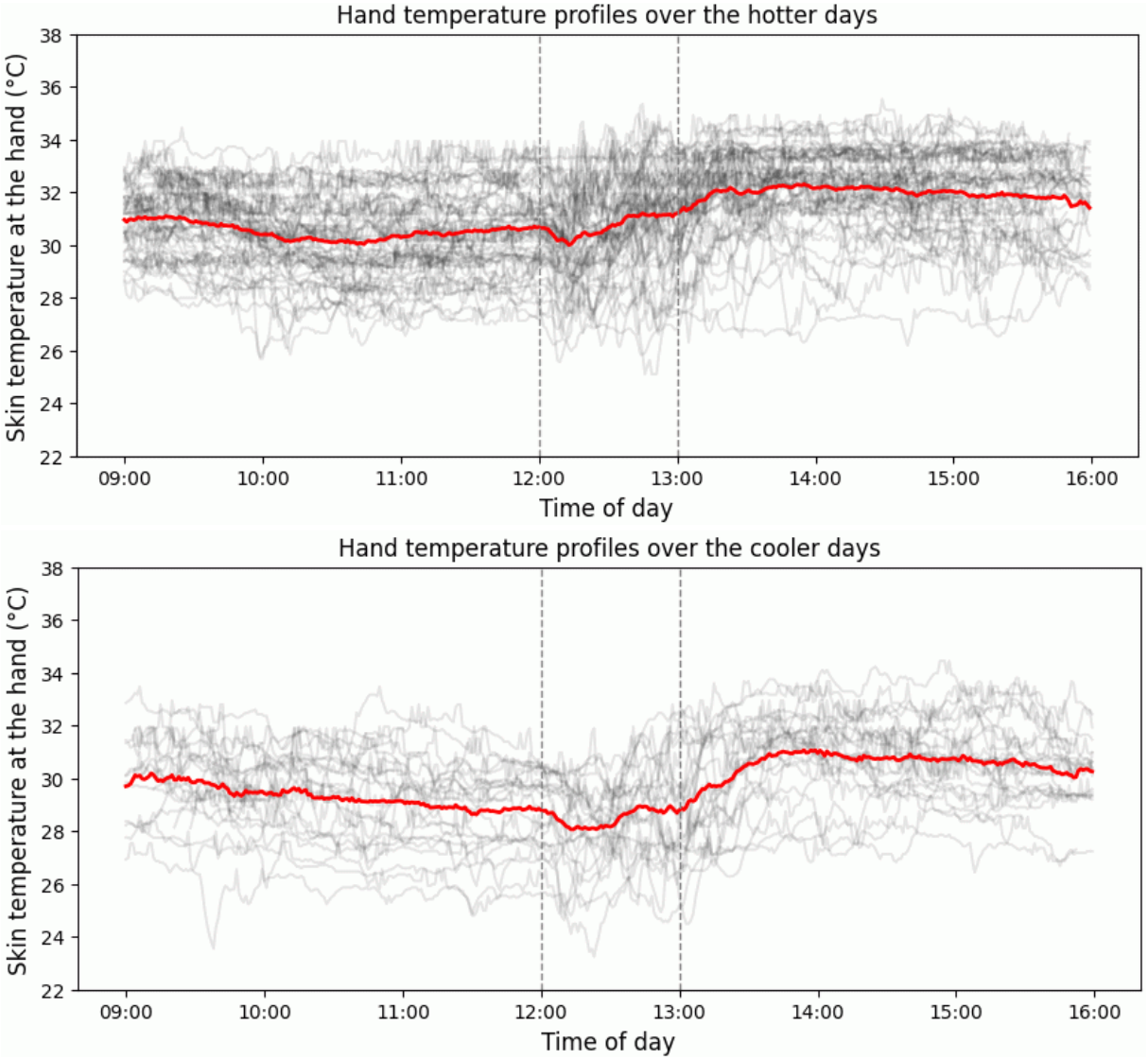
Figure 3: Hand temperatures measured during autumn and winter.



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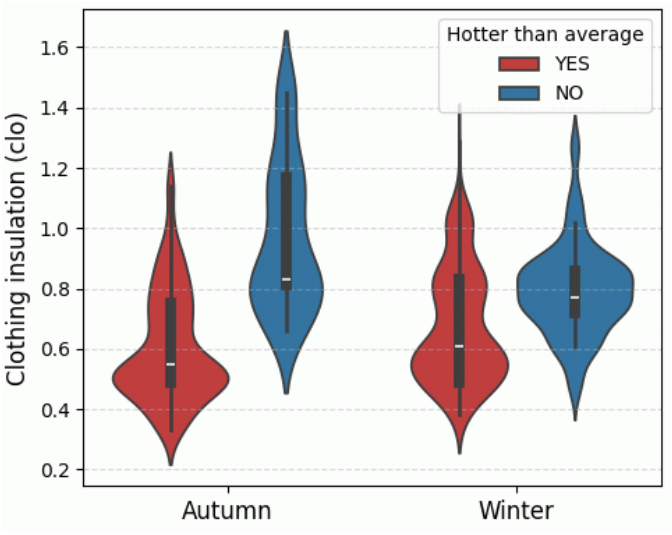
BEHAVIORAL ADAPTATIONS

The results indicate that even during autumn and winter, occupants actively adjust their behavior in response to hotter-than-average outdoor conditions, demonstrating a high degree of short-term behavioral adaptability despite the presence of well-defined seasonality. Clothing insulation levels were significantly lower on hotter days within both seasons, as shown in Figure 4, suggesting that occupants do not necessarily rely on fixed seasonal expectations but instead respond dynamically to transient thermal conditions that deviate from typical climatic patterns. Overall clo levels were significantly lower during hotter days compared to cooler ones (Autumn: −0.26 clo, $p < 0.001$; Winter: −0.11 clo, $p < 0.001$). The high variability aligns with previous full-year studies in the same climate [13]. These findings emphasize the importance of providing occupants with flexible dress codes and adaptive opportunities, particularly in mixed-mode buildings, where behavioral adjustments constitute a primary mechanism for maintaining thermal comfort.

Figure 4: Clothing insulation observed during autumn and winter.



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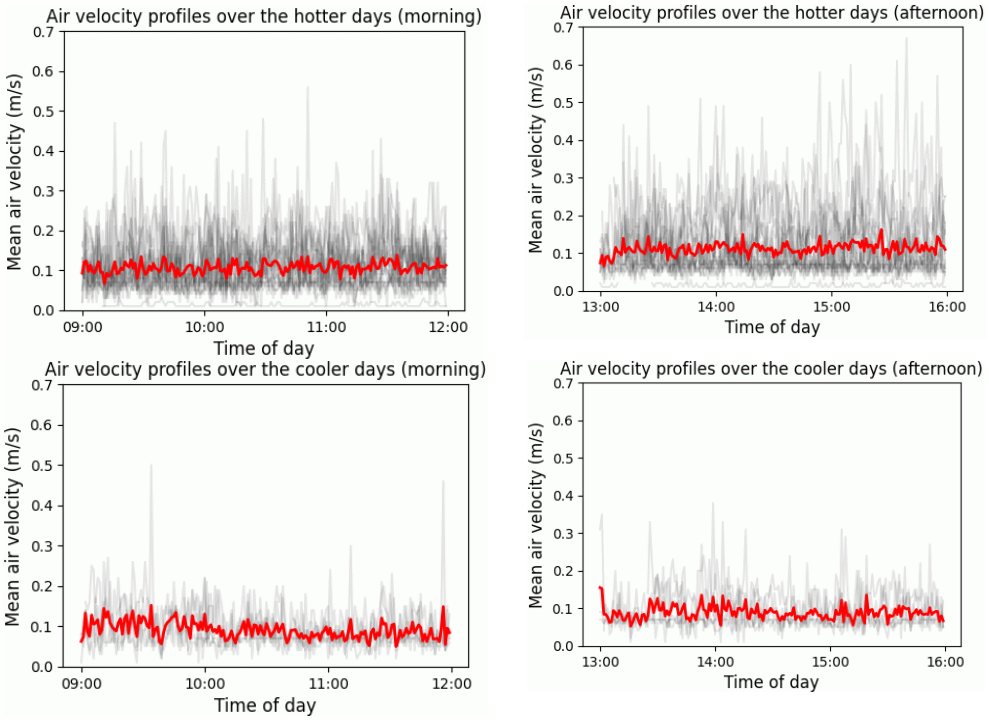
In parallel, higher indoor air velocities observed during hotter days reflect increased use of natural ventilation strategies, likely through operable windows. Figure 5 shows the measurements performed in autumn and winter grouped by the outdoor conditions. Statistical models confirmed higher air velocities during hotter days compared to cooler ones, as follows: 0.02 m/s higher ($p \approx 0.000$) in the morning and 0.04 m/s higher ($p \approx 0.000$) in the afternoon.

The presence of measurable differences in air speed during both morning and afternoon periods indicates that occupants actively modify their environment even outside warmer seasons. These results support the notion that personal control over ventilation remains effective beyond traditionally warm seasons in subtropical regions, reinforcing the relevance of mixed-mode strategies under increasingly variable climatic conditions. Therefore, guaranteeing accessible, easy-to-operate, and flexible building interfaces, as suggested by the scientific literature to support occupant behavior [14], appears to be an effective strategy not only for seasonal comfort optimization but also for coping with climate anomaly-driven thermal exposure. In the present study, such adaptive opportunities were provided through operable windows and intuitive ventilation controls, embedded within a shared workspace where occupants could freely communicate and coordinate actions to adjust the indoor environment.

Figure 5: Indoor air velocities during autumn and winter.



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PERCEPTUAL ADAPTATIONS

Outdoor thermal anomalies also affected occupants' thermal perception during autumn and winter. Rather than producing a uniform response, our results show that the direction and magnitude of this effect depended on the analytical assumption adopted (Figure 6). When thermal perception was modeled as a response to indoor conditions, implicitly assuming an environment-driven process, a pronounced shift in thermal neutrality toward cooler environments was observed on hotter days. Under this assumption, the preferred Standard Effective Temperature (SET) decreased from 26.92 °C on regular days to 25.03 °C on hotter days, suggesting a heightened sensitivity to warmth and indicating a potentially increased demand for cooling despite the typically mild seasonal context.

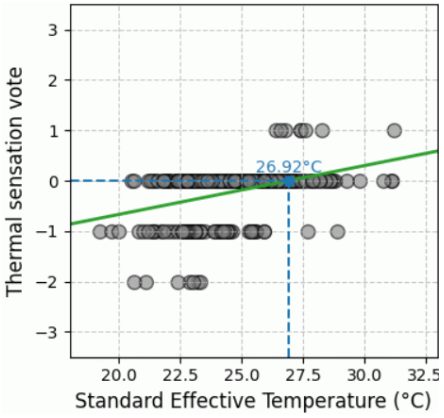
In contrast, when indoor thermal conditions were treated as a response to occupants' thermal perception, which reflects the temperatures occupants actively seek when performing behavioral adjustments, a different pattern emerged. Under this occupant-centric assumption, preferred SET increased slightly on hotter days, from 24.87 °C to 25.50 °C. This suggests that when occupants are able to perform adaptive actions, such as clothing adjustments or natural ventilation optimizations through window control, target indoor temperatures remain comparatively stable, even during warmer-than-average periods. In this sense, behavioral adaptation appears to buffer the direct impact of outdoor thermal anomalies on indoor comfort preferences. Additionally, the divergence on the outcomes according to the modelling strategy adopted aligns with recent discussions regarding causality direction in building-science research [15],

highlighting the importance of explicitly stating analytical assumptions in comfort studies.

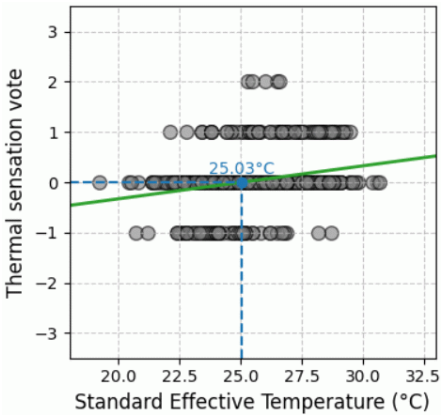
The divergence between these two perspectives is particularly relevant in mixed-mode offices during autumn and winter, when thermal expectations are less rigid than in peak summer conditions. During these traditionally cooler seasons, where occupants in Southern Brazil do not necessarily rely on air-conditioning use [16], occupants may tolerate a wider range of indoor temperatures while simultaneously engaging in adaptive behavior through both behavioral and environmental adjustments. These results indicate that analytical frameworks that overlook occupant agency may overestimate cooling demand, whereas adaptive formulations better capture the stability of thermal preferences under seasonally mild yet climatically anomalous conditions.

Figure 6: Neutral temperatures considering the following assumptions: a) and b) thermal perceptions as a response to SET; and c) and d) SET as a response to thermal perceptions.

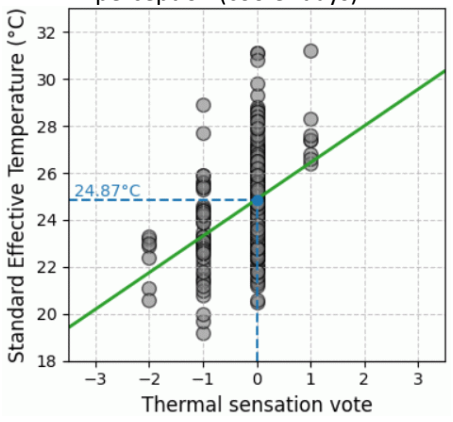
a) Occupants' thermal perception as a response to SET (cooler days)



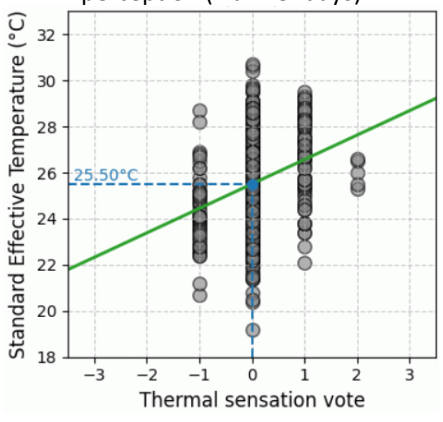
b) Occupants' thermal perception as a response to SET (warmer days)



c) SET as a response to occupants' thermal perception (cooler days)



d) SET as a response to occupants' thermal perception (warmer days)



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CONCLUSIONS

This study examined physiological, behavioral, and perceptual adaptations to warmer-than-average conditions during autumn and winter in a mixed-mode office building

under the influence of the 2023 El Niño anomaly. The assessments were performed in Florianópolis, southern Brazil, which represents a subtropical climate. Although these seasons are typically considered thermally mild, the results show that outdoor thermal anomalies produced measurable responses across all three domains, observed while occupants were indoors.

Physiological indicators revealed consistent involuntary thermoregulatory responses on hotter days, including increases in mean and localized skin temperatures at distal locations, with the strongest effects observed during lunch breaks. In all the cases, statistical analyses confirmed the higher values on skin temperatures observed. Behavioral adaptations were also evident, as occupants reduced clothing insulation and increased indoor air movement through natural ventilation, indicating active engagement with available control opportunities even outside summer conditions.

Perceptual responses showed that inferred thermal neutrality depended strongly on the analytical assumption adopted. When thermal perception was treated as a response to indoor conditions, a pronounced shift toward cooler preferred temperatures was observed on hotter days. In contrast, an occupant-centric framing, in which indoor thermal conditions were treated as a response to occupants' thermal sensations, suggested comparatively stable target temperatures. This divergence highlights the importance of explicitly considering occupant agency when interpreting thermal-comfort responses during seasonal anomalies. In a broader perspective, this interpretation may be expanded to placing behavioral opportunities to adapt to climate anomalies in a central position in shared offices, where multiple preferences occur concurrently.

Overall, the findings indicate that during autumn and winter, mixed-mode offices can accommodate short-term thermal anomalies through a combination of involuntary physiological responses and voluntary adaptive actions performed by the occupants. Analytical approaches that account for these adaptive mechanisms provide a more nuanced understanding of cooling demand during unseasonal warm periods, particularly in climates characterized by high thermal variability.

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REFERÊNCIAS

[1] W. Cai, M.J. McPhaden, A.M. Grimm, R.R. Rodrigues, A.S. Taschetto, R.D. Garreaud, B. Dewitte, G. Poveda, Y.-G. Ham, A. Santoso, B. Ng, W. Anderson, G. Wang, T. Geng, H.-S. Jo, J.A. Marengo, L.M. Alves, M. Osman, S. Li, L. Wu, C. Karamperidou, K. Takahashi, C. Vera, Climate impacts of the El Niño–Southern Oscillation on South America, Nat Rev Earth Environ 1 (2020) 215–231. https://doi.org/10.1038/s43017-020-0040-3.

[2] EPAGRI, Agricultural Research and Rural Extension Company of Santa Catarina. Calor fora de época com quebra recorde de temperatura em SC, 2023. https://ciram.epagri.sc.gov.br/index.php/2023/08/24/calor-fora-de-epoca-com-quebra-recorde-de-temperatura-em-sc/.

[3] INMET, Brazilian National Institute of Meteorology. Ano de 2023 é o mais quente da série histórica no Brasil, 2024. https://portal.inmet.gov.br/noticias/ano-de-2023-%C3%A9-o-mais-quente-da-hist%C3%B3ria-do-brasil.

[4] S. Carlucci, L. Bai, R. De Dear, L. Yang, Review of adaptive thermal comfort models in built environmental regulatory documents, Building and Environment 137 (2018) 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053.

[5] H. Djamila, Indoor thermal comfort predictions: Selected issues and trends, Renewable and Sustainable Energy Reviews 74 (2017) 569–580. https://doi.org/10.1016/j.rser.2017.02.076.

[6] R.F. Rupp, J. Kim, J. Toftum, G. Brager, R. De Dear, Ten questions concerning the application of adaptive thermal comfort in mixed-mode buildings, Building and Environment 284 (2025) 113490. https://doi.org/10.1016/j.buildenv.2025.113490.

[7] R.J. Cureau, I. Pigliautile, A.L. Pisello, M. Bavaresco, C. Berger, G. Chinazzo, Zs. Deme Belafi, A. Ghahramani, A. Heydarian, D. Kastner, M. Kong, D. Licina, A. Luna-Navarro, A. Mahdavi, A. Nocente, M. Schweiker, M. Vellei, A. Wang, Bridging the gap from test rooms to field-tests for human indoor comfort studies: A critical review of the sustainability potential of living laboratories, Energy Research & Social Science 92 (2022) 102778. https://doi.org/10.1016/j.erss.2022.102778.

[8] A.L. Pisello, I. Pigliautile, M. Andargie, C. Berger, P.M. Bluyssen, S. Carlucci, G. Chinazzo, Z. Deme Belafi, B. Dong, M. Favero, A. Ghahramani, G. Havenith, A. Heydarian, D. Kastner, M. Kong, D. Licina, Y. Liu, A. Luna-Navarro, A. Mahdavi, A. Nocente, M. Schweiker, M. Touchie, M. Vellei, F. Vittori, A. Wagner, A. Wang, S. Wei, Test rooms to study human comfort in buildings: A review of controlled experiments and facilities, Renewable and Sustainable Energy Reviews 149 (2021) 111359. https://doi.org/10.1016/j.rser.2021.111359.

[9] W. Liu, Z. Lian, Q. Deng, Y. Liu, Evaluation of calculation methods of mean skin temperature for use in thermal comfort study, Building and Environment 46 (2011) 478–488. https://doi.org/10.1016/j.buildenv.2010.08.011.

[10] ANSI/ASHRAE, American National Standards Institute Definition. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Thermal Environmental Conditions for Human Occupancy - ASHRAE 55-2023, (2023).

[11] NOAA, National Weather Service. Warm (EL Niño/Southern Oscillation - ENSO) Episodes in the Tropical Pacific, 2012. https://cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.shtml.

[12] L.P. De Souza, M.K. Bracht, M. Bavaresco, M.S. Geraldi, N.H. Gapski, K. Boudier, A.P. Melo, S. Hoffmann, Thermal sensation and adaptation after spatial transition: A review and meta-analysis, Building and Environment 258 (2024) 111585. https://doi.org/10.1016/j.buildenv.2024.111585.

[13] R.D. Vecchi, R. Lamberts, C.M. Candido, The role of clothing in thermal comfort: how people dress in a temperate and humid climate in Brazil, Ambient. Constr. 17 (2017) 69–81. https://doi.org/10.1590/s1678-86212017000100124.

[14] J.K. Day, C. McIlvennie, C. Brackley, M. Tarantini, C. Piselli, J. Hahn, W. O'Brien, V.S. Rajus, M. De Simone, M.B. Kjærgaard, M. Pritoni, A. Schlüter, Y. Peng, M. Schweiker, G. Fajilla, C. Becchio, V. Fabi, G. Spigliantini, G. Derbas, A.L. Pisello, A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Building and Environment 178 (2020) 106920. https://doi.org/10.1016/j.buildenv.2020.106920.

[15] R. Sun, S. Schiavon, G. Brager, E. Arens, H. Zhang, T. Parkinson, C. Zhang, Causal thinking: Uncovering hidden assumptions and interpretations of statistical analysis in building science, Building and Environment 259 (2024) 111530. https://doi.org/10.1016/j.buildenv.2024.111530.

[16] R. Forgiarini Rupp, E. Ghisi, Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate, Energy and Buildings 144 (2017) 152–166. https://doi.org/10.1016/j.enbuild.2017.03.039.