DOI: 10.61782/fa.2025.0896

FORUM ACUSTICUM EURONOISE 2025

THERMO-ACOUSTIC PERCEPTION IN AN OPEN-PLAN OFFICE: INFLUENCE OF VENTILATION, GENDER, AND HEADPHONES UNDER SIMILAR THERMAL CONDITIONS

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ABSTRACT

This study evaluates differences in acoustic annoyance and thermal sensation in an open-plan office under natural ventilation and artificial air conditioning during summer. The office has 36 workstations, located in Florianópolis, Brazil, in a hot and humid climate. The field study occurred over four days in January 2024 and involved 14 participants (8 male, 6 female). Sound pressure level, air temperature, relative humidity, globe temperature, and air velocity were measured continuously. Participants wore similar clothing, performed similar office activities, and could not use headphones. They answered questionnaires on thermal sensation and acoustic annoyance every 20–30 minutes, specifying the noise source and their preferred headphone use mode if allowed. Results show that NV days led to cooler sensations, while AC days resulted in warmer perceptions. Noise annoyance varied: outdoor noise was more disturbing under NV, whereas HVAC noise, thermal PECS, and unintelligible speech were more prominent under AC. Females reported higher annoyance from colleagues' PECS, walking, and speech. Overall, 53% preferred using headphones, primarily for masking, while 47% preferred not to use them, especially on AC days. These findings highlight the interaction between thermal and acoustic perception and the need for adaptive strategies to improve workplace comfort.

Keywords: *noise annoyance, thermal sensation, acoustic PECS, thermal PECS, mixed-mode*

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1. INTRODUCTION

Passive design strategies, such as natural ventilation, maintain indoor comfort without energy consumption, play a crucial role in climate adaptation. Natural ventilation can reduce cooling demand in advanced economies; however, in hot climates, it often leads to an increased reliance on mechanical cooling as cooling degree days continue to rise [1]. Mixed-mode buildings, which combine natural and mechanical ventilation, offer an effective strategy for energy efficiency [2].

While energy efficiency is vital, indoor environmental quality (IEQ) must also be considered, particularly in workplaces where thermal and acoustic conditions impact workers' well-being and productivity [3]. Thermal dissatisfaction is closely linked to a lack of personal control over the environment [4]. People generally tolerate a wider range of temperatures in naturally ventilated spaces compared to those in mechanically conditioned environments [2,5]. Mixed-mode buildings enhance thermal comfort by promoting adaptive behaviors and providing occupants with a greater sense of control [6]. Additionally, personal environmental control systems (PECS), such as electric fans, help mitigate heat-related stress [7].

Noise annoyance is another critical issue in open-plan offices [4,8]. Unpredictable and uncontrollable noise is particularly disruptive [3], whereas steady background noise, such as equipment sounds, is less intrusive [4,8]. Despite the significant impact of acoustic discomfort on workplace performance [9,10], research on in-situ acoustic assessments remains limited [11]. Notably, natural ventilation is rarely considered a source of acoustic discomfort in office environments.

Recent research has explored the intersection of thermal and acoustic environments. The noise generated by PECS, such as fans, has been identified as a significant factor influencing their usage [12]. Moreover, operative temperature has been shown to affect noise perception and overall acoustic comfort [13]. Additionally, indoor satisfaction is influenced by the combined effects of noise and thermal conditions [14]. Gender differences also play a role in how individuals experience thermal and acoustic environments [15].

Personal control is a crucial determinant of workplace satisfaction, reducing stress and enhancing comfort [3]. Mixed-mode buildings, which offer flexible ventilation options, support this control. Furthermore, advancements in acoustic PECS, such as noise-cancelling headphones and active sound zoning technologies, could transform the perception of indoor acoustic environments [16].

Despite the growing recognition of thermal-acoustic interactions, further studies are necessary to assess their impact on real-world office environments [17,18]. Monitoring workplace conditions over extended periods, combined with occupant feedback [3], would provide valuable insights into the complex relationships between thermal and acoustic comfort [8].

This study evaluates differences in thermal and acoustic perception in an open-plan office under different indoor conditions, such as natural ventilation and artificial air conditioning during summer.

2. METHOD

The following sections describe the indoor environment and the measurement methods and then outline the experiment procedure of the field study.

2.1 Characterization of the climate and the open-plan office

Florianópolis is characterized by a hot and humid climate, classified as Zone 2A according to ASHRAE 169 [19] and as a mild temperature, fully humid climate with hot summers (Cfa) under the Köppen-Geiger classification [20].

The office under study is located on the top (fourth) floor of the building, with a total floor area of approximately 153 m² and a ceiling height of 2.6 m. The workspace consists of 36 workstations, two façades (northwest and southeast), and roof exposure. Interior finishes include ceramic floor tiles, a ceiling insulated with glass wool, and white hard walls. The furniture is composed of medium-density fiberboard (MDF) with a wood-tone finish.

The building's surroundings predominantly feature vegetation and hills, with no direct exposure to street-facing façades. Background noise levels in the office were assessed in accordance with ISO 11690-1:2020 [21]. Measurements indicated that under artificial air conditioning set to 26°C, the background noise level did not exceed 36 dBA. With the HVAC system turned off, the maximum recorded level was 33 dBA. Both measuremenrs occurred during the night. When all windows were open (measurements occurred really early in the morning), background noise levels ranged between 36 and 45 dBA (in the absence of additional interferences), with peak values recorded near the open windows.

2.2 Data collection

Environmental data related to thermal variables and noise levels were collected throughout all study days. Acoustic measurements followed the guidelines outlined in ISO 22955:2021 Annex E [22], with the sound level meter positioned at a height of 1.20 m above the floor and equivalent noise levels continuously recorded. The acoustic parameters utilized to characterize each experimental day comprised the equivalent continuous noise level (LA,eq,3h), representing the averaged noise level over the entire measurement period. Additionally, the L90 parameter was employed to denote the noise level exceeded 90% of the time, often regarded as the background noise level. The L50 value corresponded to the noise level surpassed 50% of the time, while L10 indicated the noise level exceeded 10% of the time, typically associated with peak noise levels. Lastly, the noise climate (NC) was defined as the difference between L10 and L90, providing insight into the variability of noise levels throughout the measurement period.

Thermal variables were also continuously measured during the entire field study, including air temperature, air velocity (measured at three heights and averaged), globe temperature, and relative humidity. Mean values for each variable were considered as indicators for each morning, with air temperature additionally characterized by its maximum and minimum values achieved.

2.3 Questionnaire

An online questionnaire was employed to gather subjective responses. Before the field study began, participants completed an initial questionnaire covering personal characteristics such as age, height, weight, gender, and education level.

Noise annoyance was assessed using a 5-point scale in accordance with ISO 22955:2021 and ISO 15666:2022, ranging from 1 (not at all) to 5 (extremely). Participants evaluated annoyance levels for ten noise sources, adapted from ISO 22955:2021 [22]: external noise, HVAC noise, general equipment noise (e.g., computers, printers), their own thermal PECS, colleagues' thermal PECS, unintelligible and intelligible conversations, people walking nearby, noise linked to human activity, and noise associated with a specific person.

Thermal sensation was evaluated using a 7-point scale, according to ASHRAE 55 [23]: -3 cold;-2 cool; 1 slightly cool; 0 neutral; +1 slightly warm; +2 warm; and +3 hot. Thermal preference was also evaluated using a 7-point scale: -3 much cooler; -2 cooler; -1 slightly cooler; 0 without change; +1 slightly warmer; +2 warmer; and +3 much warmer.

Additionally, participants were asked about their use of acoustic PECS, specifically whether they could use headphones (HP) and their preferred mode of use. The available options included: listening to music (Masking - music), listening to colored noise (Masking - color noise), using active noise cancelling (ANC), using ANC combined with music (ANC + Masking), wearing headphones without any function (Just HP), or opting not to use them (No HP).

2.4 Participants

The participants consisted of researchers working in the office, all of whom were familiar with the environment. Fourteen researchers (eight male, six female) voluntarily participated in the field study. The sample included six undergraduate students, five PhD candidates, two master's students, and one postdoctoral researcher. The participants' mean age was 26.5 years (±4.5), with a mean height of 1.72 m (±0.08 m) and a mean weight of 68.64 kg (±7.26 kg), resulting in a mean BMI of 23.11 (±2.15). To maintain consistency, all participants wore the same type of clothing, and we considered typical ensembles of trousers and short-sleeve shirt (clo = 0.57) plus a standard office chair (clo = 0.10), resulting in a clo value of 0.67 [23]. The metabolic rate was classified as office activity, primarily typing (met = 1.1 [23]).

2.5 Procedure

The field study took place during January 2024 (summer) over four mornings (23/01, 24/01, 25/01, and 31/01). Participants retained control over their thermal PECS but did not use any acoustic PECS to avoid altering their perception of the acoustic environment.

Two field study days were conducted under artificial conditioning at a setpoint of 26°C (AC days), while the other two days were conducted under natural ventilation (NV days) with all windows open. Each field study session lasted a maximum of three hours.

Environmental data collection was continuous throughout the study. Before beginning the experiment, participants completed the initial characterization questionnaire. Subsequently, subjective evaluations were recorded through questionnaires administered at intervals of 10 to 30 minutes after participants began working.

A total of 138 subjective responses were collected, with 48% corresponding to NV conditions and 52% to AC conditions. Participants were instructed to wear the same type of clothing (clo = 0.67), refrain from online meetings, and avoid using headphones during the experiment. Additionally, some participants had access to thermal PECS, including desk fans and desk evaporative coolers, which were powered via USB connections to their computers. Tab. 1 provides an overview of the thermal PECS available [12].

Table 1. Thermal PECS description (adapted from [12]).

Thermal PECS (desk)	Fan	Evaporative cooler
Power (W)	3	10
Dimension (cm)	15x15x12	17x17x17
Noise level (dBA)	42	40-54
Air velocity (m/s)	1.17	0.81-1.78
Picture		

2.6 Statistical analysis

As the dataset for acoustic annoyance votes did not follow a normal distribution, and each participant rated ten noise sources, a Friedman test was conducted to determine whether significant differences existed among noise sources ($p < 0.05$). For noise sources where significant differences were identified, pairwise comparisons were performed using the Wilcoxon signed-rank test to assess statistical significance ($p < 0.05$), with Bonferroni correction applied to adjust for multiple comparisons.

Subsequently, Mann-Whitney U tests were applied to compare mean annoyance ratings across different factors, including gender, willingness to use headphones, and ventilation type, for each noise source. Given the non-normal distribution of votes, differences were evaluated at three levels of statistical significance: 5% ($p < 0.05$), 1% ($p < 0.01$), and 0.1% ($p < 0.001$). The same statistical approach was applied to analyze thermal perception votes.

3. RESULTS

3.1 Environmental variables

The outdoor thermal conditions, specifically the mean air temperature (Air T) and relative humidity (RH), were evaluated for the morning period (8 a.m. to 12 p.m.) based on data provided by EPAGRI (Company of Agricultural Research and Rural Extension of Santa Catarina). Tab. 2 presents the recorded thermal conditions for each field study in the morning. The study included two mornings under natural ventilation (NV1 and NV2) and two mornings with the air conditioning system operating at a setpoint of 26°C (AC1 and AC2).

Table 2. Outdoor thermal conditions (mean values for 08:00-12:00).

Indicator	NV1	NV2	AC1	AC2
Air T (°C)	22.8	24.2	24.6	27.2
RH (%)	82.0	68.7	69.1	73.2

The mean outdoor temperatures during the field study varied between 22.8°C and 27.2°C, with NV2 and AC1 exhibiting similar mean outdoor air temperatures. Additionally, these two field study days shared comparable mean outdoor relative humidity levels, both close to 69%. In contrast, NV1 and AC2 differed not only in terms of mean outdoor air temperature but also in mean relative humidity, with an observed difference of 8.8%, both exceeding the values recorded for NV2 and AC1.
Outdoor thermal conditions can influence individuals' expectations of indoor environments upon arrival in spaces intended for prolonged occupancy, such as offices or homes. These conditions may also affect the time required for thermal adaptation to indoor environments. Therefore, only thermal and acoustic perception votes collected after the acclimatization period were considered in the analysis.
Moreover, indoor thermal conditions play a fundamental role in shaping individuals' overall environmental perception after transitioning from outdoor conditions, whether extreme or moderate. As such, indoor thermal conditions are critical when evaluating both thermal and acoustic perception. Tab. 3 presents the thermal indicators characterizing the indoor environment across the days.

Table 3. Indoor thermal conditions.

Indicator	NV1	NV2	AC1	AC2
Air T máx (°C)	25.4	25.7	26.0	26.4
Air T mean (°C)	24.9	25.3	25.1	25.2
Air T min (°C)	24.3	24.7	24.1	24.2
Globe T (°C)	25.1	25.7	25.5	25.6
Air V (m/s)	0.2	0.2	0.2	0.2
RH (%)	65.0	57.8	60.7	65.8

The mean indoor air temperature across the four field study days exhibited minimal variation, with differences not exceeding 0.4°C. Similarly, the variation in minimum air temperature remained below 0.5°C. While the maximum air temperature varied by 1°C between the lowest and highest recorded values, the highest temperature did not exceed 26.5°C. The maximum difference in mean globe temperature (Globe T) was approximately 0.6°C, and the mean air velocity (Air V) remained consistent. In contrast, relative humidity exhibited greater variation, ranging from 57.8% to 65.8%.
The indoor acoustic conditions were also analyzed based on key indicators (L10, L50, L90, and LAeq,3h), as presented in Tab. 4. The equivalent noise levels recorded ranged between 48 and 52 dBA, with background noise levels (L90) remaining below 45 dBA on all study days, while L10 values were equal to or above 50 dBA. Notably, the noise climate (NC = L10 – L90) exceeded 10 dBA only on AC1, suggesting a potential source of variability that warrants further investigation.

Table 4. Indoor acoustic conditions.

Indicator	NV1	NV2	AC1	AC2
L10	50	53	54	54
L50	46	49	48	46
L90	42	45	41	44
LA,eq,3h	48	50	52	51

Given that Shapiro-Wilk tests indicated a non-normal distribution for all measured variables (noise level and air temperature), Mann-Whitney U tests were conducted to assess statistical differences. A preliminary analysis revealed that the two natural ventilation days (NV1 and NV2) differed significantly in both air temperature and noise level ($p < 0.001$). Therefore, to enable meaningful comparisons between thermal and acoustic perception under natural ventilation and air-conditioned conditions, it was necessary to verify whether NV1 and NV2 aligned statistically with the AC days.
Regarding air temperature, no significant differences were found between NV1 and both AC1 and AC2 ($p > 0.05$), nor between NV2 and both AC1 and AC2 ($p > 0.05$). Similarly, for noise levels, NV1 and AC2, as well as NV2 and AC1, were not significantly different ($p > 0.05$). Additionally,

occupancy levels during the field study days remained relatively stable, ranging from 8 to 13 individuals.

3.2 Thermal sensation responses

The overall distribution of thermal sensation votes indicates that the majority of participants (78%) reported a neutral thermal sensation, which aligns with the indoor thermal conditions. Temperature values predominantly ranged between 24°C and 26°C, with a mean air velocity of 0.2 m/s and a mean relative humidity between 57% and 66%.
However, when considering only natural ventilation (NV) days, the percentage of neutral sensation votes increased to 80%, with very few responses indicating a warmer sensation (2%). In contrast, during air-conditioned (AC) days, neutral sensations accounted for 76% of the votes, while 17% reflected a warmer sensation (> 0). Thermal sensation ratings differed significantly between AC and NV days ($p < 0.001$), with a mean thermal sensation of -0.17 for NV days and 0.12 for AC days.
No statistically significant differences in thermal sensation votes were observed between male and female participants or between individuals seated close to the window and those seated farther away.
The majority of cooler sensation votes on NV days were associated with a preference to maintain the existing thermal conditions, a trend also observed in the few cooler sensation votes recorded during AC days. However, none of the participants who reported a warmer sensation under AC conditions indicated a preference to remain in that state.

3.3 Noise annoyance responses

Across all four field study days, the highest mean noise annoyance was associated with activity-related sounds generated by people. This was the only noise source with a mean annoyance rating exceeding 2 and was significantly higher than all other sources of annoyance ($p \approx 0$).
Noise sources such as outdoor sounds, thermal PECS (both from others and the participant's own), and equipment were the second most prominent sources of annoyance, with mean ratings close to 1.5. In contrast, sources including air conditioning (HVAC), speech (both intelligible and unintelligible), people walking, and noise from a specific individual were rated with a mean annoyance level close to 1, indicating low levels of disturbance.
Among noise sources related to human activity, only general activity of people resulted in statistically significant annoyance. Additionally, among equipment-related noise sources, the HVAC system was the only one with a significantly low annoyance rating.

3.3.1 Ventilation type

Noise annoyance ratings were analyzed separately for natural ventilation (NV) and air-conditioned (AC) days. The two datasets were compared for each noise source using Mann-Whitney U tests, with significance levels set at (*) $p < 0.05$, (**) $p < 0.01$, and (***) $p < 0.001$. Fig. 1 presents the mean noise annoyance values for each source under both ventilation conditions, along with the statistical significance of the comparisons.

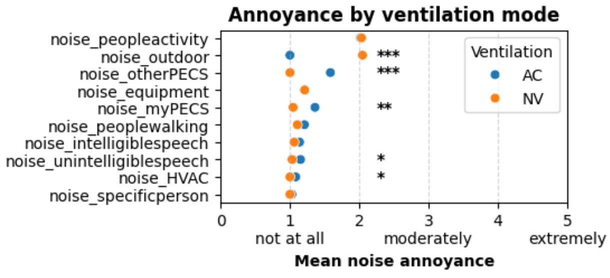

Figure 1. Noise annoyance by ventilation mode.

No significant differences were observed in annoyance related to general activity of people or equipment, suggesting that variations in measured noise levels between AC and NV days were not necessarily associated with differences in human activity or office equipment usage.
Outdoor noise was the only source for which annoyance ratings were significantly higher under natural ventilation compared to AC days. In contrast, all other noise sources exhibited higher mean annoyance levels under AC conditions, with statistically significant differences observed for noise from thermal PECS (both the participant's own and those of colleagues), the HVAC system, and unintelligible speech.
One possible explanation is that outdoor noise may serve as a masking effect, reducing the perceptibility of other noise sources and thereby minimizing disturbance. Consequently, closing the windows could enhance the acoustic perception of the indoor open-plan office environment, leading to greater annoyance.
Additionally, thermal sensation under AC conditions tended to be skewed toward a warmer perception, which could have increased the use of thermal PECS compared to NV days, despite similar thermal conditions. While 72% of votes under AC conditions indicated no use of thermal PECS, this proportion rose to 95% under NV conditions.
Thus, the increased noise levels observed on AC days may be associated with the greater reliance on thermal PECS, driven by a higher perceived need for thermal adjustments.

3.3.2 Gender

Overall, female participants reported higher mean noise annoyance ratings compared to males. However, significant differences were observed for specific noise sources, with females reporting significantly higher annoyance levels related to activity of people, people walking, colleagues' use of thermal PECS (all $p < 0.001$), and unintelligible speech ($p < 0.05$). Fig. 2 shows these results.

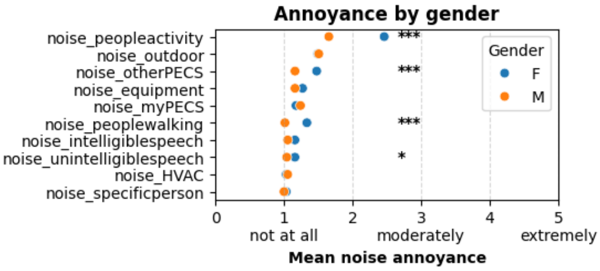

Figure 2. Noise annoyance by gender.

Notably, the highest annoyance rating recorded in the study was among females regarding activity of people, with a mean value approaching 2.5, indicating a level of annoyance between "slightly" and "moderately" annoyed.
The greater annoyance reported by females regarding colleagues' use of thermal PECS can be attributed to differences in PECS usage between genders. Among male participants, 15% of votes indicated the use of an evaporative cooler, while 80% reported not using any thermal PECS. In contrast, 87% of female votes indicated no use of thermal PECS, suggesting that they were more susceptible to perceiving and being disturbed by their colleagues' PECS, particularly those used by male participants. This also explains why the only noise source for which males reported higher mean annoyance ratings was their own thermal PECS, although this difference was not statistically significant.
No significant gender-based differences were found for noise annoyance ratings related to outdoor or HVAC noise.

3.3.3 Thermal sensation

Thermal sensation votes were categorized into three groups: neutral sensations (sensation votes = 0), cooler sensations (sensation votes < 0), and warmer sensations (sensation votes > 0).
Across all noise sources, mean noise annoyance ratings associated with neutral thermal sensations were never the highest when compared to either cooler or warmer sensations. As expected, since higher annoyance from outdoor noise was predominantly reported during natural ventilation—when thermal sensation votes tended to be cooler—cooler sensations in this study were also associated with greater annoyance from outdoor noise. Similarly, annoyance related to participants' own thermal PECS was higher when they reported experiencing cooler sensations, likely due to the use of these PECS to mitigate discomfort. However, when comparing cooler sensations to neutral sensations, the only noise source for which annoyance was significantly higher in the cooler group was participants' own thermal PECS ($p < 0.05$), likely influenced by the use of evaporative coolers. This suggests that participants may have been willing to tolerate increased noise annoyance from their PECS in exchange for thermal comfort.
Conversely, mean noise annoyance ratings were generally higher when participants experienced warmer thermal sensations. This finding aligns with expectations, as warmer sensations were predominantly reported on air-conditioned (AC) days, during which mean noise annoyance was higher for seven out of the ten noise sources. Consequently, it was expected that warmer sensations—associated with AC operation—would correspond with significantly higher overall noise annoyance.
However, interestingly, when comparing the neutral and warmer sensation groups, significant differences in noise annoyance were only observed for specific sources: annoyance from colleagues' thermal PECS ($p < 0.001$), the HVAC system, and intelligible speech (both $p < 0.01$). Additionally, AC days also showed significant differences in annoyance related to participants' own thermal PECS ($p < 0.01$) and unintelligible speech ($p < 0.05$), but not for intelligible speech.

3.3.4 Acoustic PECS

Mean acoustic annoyance ratings were higher for nearly all noise sources among participants who indicated a preference for using headphones, except for HVAC noise. However, these differences were statistically significant only for specific noise sources, including activity of people ($p < 0.001$), as well as outdoor noise and HVAC noise (both $p < 0.01$).
When analyzing noise annoyance in relation to preferred headphone mode, results indicate that whenever mean noise annoyance ratings reached or exceeded 2 (slightly annoyed), participants expressed a preference for using headphones with some form of masking—whether through color noise, music, or a combination with active noise cancellation (ANC). The only exception was annoyance from activity of people, for which ANC alone was not a preferred option.

Among all responses regarding headphone use preferences, 53% of votes indicated that participants would prefer using headphones in some capacity. Of these, 33% preferred masking (31% with music and 2% with color noise), 18% preferred ANC, and 2% preferred both ANC and masking. These findings suggest that, when participants chose to wear headphones, listening to music was the most preferred mode. However, 47% of all votes indicated a preference for not using headphones at all.

This preference for not using headphones was even more pronounced under specific conditions: during AC days (49%), when participants reported a neutral thermal sensation (49%), and among male participants (57%). A higher proportion of participants who experienced warmer sensations also preferred not to use headphones, though these responses were largely associated with AC days.

Regarding specific headphone mode preferences, ANC-only usage was more commonly reported among female participants (27% of their responses), while the preference for masking with color noise increased on days with natural ventilation (5% of the votes).

4. CONCLUSIONS

This study highlights the interrelationship between thermal perception, noise annoyance, and behavioral responses in open-plan offices. The majority of participants (78%) reported neutral thermal sensations, with significant differences between air-conditioned (AC) and natural ventilation (NV) days ($p < 0.001$). NV days were associated with cooler sensations, while AC days led to warmer sensations, with no participants preferring to remain in a warm state.

Among noise sources, activity of people caused the highest annoyance ($p < 0.0001$), followed by outdoor noise, thermal PECS, and equipment. Annoyance was significantly higher for outdoor noise on NV days, while AC conditions resulted in greater annoyance from thermal PECS, HVAC noise, and unintelligible speech. This suggests that outdoor noise may act as a masking effect, reducing perception of other sounds, while AC days heightened awareness of indoor disturbances, likely due to increased reliance on thermal PECS.

Gender differences were evident, with females reporting significantly higher annoyance related to activity of people, walking, colleagues' thermal PECS ($p < 0.001$), and unintelligible speech ($p < 0.05$). The highest annoyance recorded was among females regarding activity of people (mean ≈2.5). This could be explained by lower PECS usage among women, making them more susceptible to perceiving their colleagues' devices.

Thermal perception also influenced noise annoyance, with warmer sensations correlating with higher annoyance, particularly from colleagues' PECS ($p < 0.001$), HVAC noise, and intelligible speech ($p < 0.01$). Since AC days were associated with to warmer sensations, they also showed higher annoyance levels for most noise sources.

Regarding headphones, 53% of participants preferred using them, primarily for masking (31% with music). However, 47% preferred not to use headphones, especially on AC days (49%), among males (57%), and under neutral thermal sensations (49%).

Overall, NV settings may help reduce noise annoyance despite higher outdoor noise exposure, whereas AC conditions amplify awareness of indoor disturbances, particularly from thermal PECS. The findings emphasize the need for tailored strategies to improve both thermal and acoustic comfort in office environments.

Future research should investigate the effectiveness of noise masking solutions, including the use of headphones, in mitigating workplace noise annoyance. Additionally, further studies should assess the indoor soundscape within mixed-mode environments, considering the interaction between ventilation strategies and acoustic perception.

5. ACKNOWLEDGMENTS

This work was supported by the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES), Financing Code 001, and the National Council for Scientific and Technological Development (CNPq). Acoustic measurements were only possible with support of LVA-UFSC and financial support of FINEP.

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