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Article

A field-based methodology for thermal comfort evaluation: A case study on university classrooms

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ABSTRACT

Ensuring thermally comfortable indoor environments is essential for occupant well-being, learning performance, and energy efficiency. This study proposes a field-based methodology for the assessment of thermal comfort, aligned with international standards and designed to be reproducible and applicable across diverse building types and climatic conditions. The objective methodology integrates both objective (measurements) and subjective (surveys) methods, combined with behavioral observations, to provide a detailed assessment of indoor thermal comfort conditions. The methodology integrates long-term and short-term measurements of air temperature, mean radiant temperature, relative humidity, air velocity, and along with the calculation of PMV/PPD. The data reliability is verified through calibration, inter-device agreement, and statistical evaluation using Mean Bias Error (MBE) and coefficient of determination (R^2). Furthermore, occupant surveys and camera-based observations capture subjective perceptions and adaptive behaviors, linking measured values with real-world occupancy conditions. The proposed methodology was applied to three amphitheater-style university classrooms characterized by high window-to-wall ratios on the south-facing façade. Findings showed that thermal gradients near south windows, confirmed by surveys reporting higher dissatisfaction and reduced concentration in south façade-adjacent zones. Observations revealed limited adaptation, with windows seldom opened and curtains generally closed, and underscoring results indicated the need for passive or automated strategies. The results confirm the methodology's ability to capture spatial and temporal variations, link predictive indices to occupant perception. Overall, the study offers a standards-based methodology suitable for assessing thermal comfort in different building type and climate.

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INTRODUCTION

Thermal comfort is a well-established research focus in building science, not only due to its impact on occupant, well-being, health, cognitive performance, and productivity but also because of the increasing demand for energy efficient and climate-resilient building design (Hong et al., 2023). Recent research has increasingly emphasized occupant-centered assessment methods, integrating in-situ measurements, behavioral observations, and data-driven modeling to capture the complexity of real indoor environments (Kim, Schiavon, & Brager, 2018). Despite these advances, there is still a need for field-based methodologies that are simultaneously comply with standards, reproducible, and broadly applicable, thereby enabling reliable cross-study comparisons and supporting evidence-based design decisions across diverse building types and climatic conditions. In this context, adaptive comfort theory has provided an important counterpoint to classical laboratory-based models by recognizing the dynamic role of climate, culture, and behavioral adaptation in shaping thermal expectations (Brager & de Dear, 2001; Nicol & Humphreys, 2002).

Classical approaches such as the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models, introduced by Fanger and embedded in standards such as ASHRAE Standard 55 and ISO 7730 remain the dominant frameworks for quantifying thermal comfort (de Dear & Brager, 1998; ISO, 2025; ASHRAE, 2023). However, these models have been validated extensively in controlled laboratory settings, their direct application to real environments often encounters difficulties due to spatial non-uniformities, transient thermal condition dynamics, and variable occupant behavior. This limitation has led scholars to argue for the integration of adaptive opportunities, such as operable windows, shading, and occupant control, into predictive frameworks, since users often tolerate wider ranges of indoor conditions when provided with environmental control (Humphreys & Nicol, 2002; Schweiker & Wagner, 2016).

Recent studies have attempted to address these limitations through hybrid and adaptive strategies. For example, Kim et al. (2018) demonstrated that personalized comfort models calibrated with human-centric parameters can improve prediction accuracy in real buildings. Comparative analyses of thermal indices such as SET, UTCI, and PET have also been carried out to evaluate robustness under different environmental and cultural contexts (Jing et al., 2024). Parallel research has also examined the links between thermal comfort and other dimensions of indoor environmental quality, including daylighting and acoustics, highlighting the importance of multi-criteria frameworks (Dawe et al., 2021; Tzempelikos & Athienitis, 2007). Yet, many of these efforts remain confined to idealized test scenarios or single-case studies, restricting their generalizability.

There remains to be a need for methodologies that can be applied under real-world conditions and enable systematic comparison of indoor spaces with varying physical characteristics. Recent studies support this direction: Sun et al. (2022) proposed a portable and reproducible framework for long-term thermal comfort evaluation using a standardized data model, while Dawe et al. (2021) reported field-based evaluations of thermal and acoustic comfort in office buildings, underscoring the value of in-situ assessments. However, existing studies either propose generalized frameworks without testing in uniform buildings or examine building types with limited spatial variability, leaving a gap for methods that can compare comfort conditions across spaces with different geometries and façade features within the same building type.

Bay Şahin and Elnimeiri (2025) identified severe thermal discomfort in upper-level social housing units in hot-dry climates, primarily using diagnostic imaging and surveys. Similarly, Şuta and Zencirkıran (2024) explored occupant satisfaction in mass housing during the COVID-19 period, emphasizing the importance of indoor environmental quality but without offering a standardized measurement framework. These contributions underline the importance of empirical research in uncovering comfort-related issues in real buildings. Collectively, these studies confirm the importance of empirical field research while also exposing the absence of a coherent, widely applicable methodology for thermal comfort evaluation. Such a methodology would enable consistent comparison of results across different climate, buildings and rooms and research contexts.

To address this gap, the present research introduces a reproducible, standards-aligned, field-based methodology specifically designed for assessing indoor thermal comfort conditions under in real word building environments. The methodology integrates both objective and subjective methods, combined with behavioral observations, to provide a detailed assessment of indoor thermal comfort conditions. The methodology is aligned with international standards (ISO 7730, ASHRAE 55) and designed to be reproducible and broadly applicable. It combines long-term and short-term measurement of environmental parameters—air temperature, mean radiant temperature, relative humidity, air velocity, and PMV/PPD—with personal factors -clothing insulation and activity level. Measurement reliability is ensured through systematic device calibration, inter-device comparison, and statistical validation using Mean Bias Error (MBE) and coefficient of determination (R^2), consistent with ASHRAE Standard 14 (ASHRAE, 2023). A substantial body of research has investigated thermal comfort in educational and office environments through field measurements and simulation-based analyses; however, the majority of these studies have tended to rely exclusively on either objective environmental data or subjective comfort assessments, limiting methodological integration.

This limitation often prevents a full understanding of how occupants dynamically interact with their environments under real-world conditions. Mıhlayanlar et al. (2017) investigated thermal comfort in a higher education facility in Edirne using on-site environmental measurements. In such field studies, however, integrating information on occupant behavior and adaptive responses is also essential for interpreting comfort conditions more comprehensively. De Dear and Brager (1998) advanced the adaptive comfort framework through large-scale survey data across diverse climates, while Yao et al. (2009) and Fanger (1970) focused primarily on quantitative comfort indices, placing limited emphasis on contextual or behavioral adaptation. Although these contributions have greatly advanced the understanding of indoor environmental quality, the lack of integration between objective field measurements, subjective thermal sensation surveys, and behavioral observations still constrains the holistic interpretation of comfort in real-world settings. Therefore, this study aims to address this methodological gap by developing a comprehensive field-based evaluation framework that simultaneously captures measured environmental variables, subjective responses, and observed adaptive behaviors under actual classroom occupancy conditions to provide a more holistic interpretation of thermal comfort assessments.

Following its development, the methodology was applied in three amphitheater-style university classrooms with high window-to-wall ratios and varying façade orientations. This application enabled the identification of spatial thermal gradients, localized discomfort zones, and orientation-dependent thermal dynamics. Rather than solely reporting case-specific findings, the study demonstrates that the proposed methodology provides a reliable, generalizable framework for evaluating thermal comfort in educational buildings.

METHODOLOGY

This study develops a field-based methodology (Figure 1) for evaluating indoor thermal comfort conditions of any building type. The methodology is designed to be applied in different climates and building types, ensuring both comparability and applicability. It integrates objective (measurements) methods, subjective (surveys) methods, and behavioral observations to enable systematic assessment of thermal comfort conditions.

Before initiating data collection, the methodology prescribes a preliminary data collection phase to establish a reliable baseline for subsequent thermal comfort evaluation.

As a first step, architectural, technical references, including architectural drawings, and façade details, should be reviewed to define the geometry, constructional characteristics and environmental control systems. This reference information is then supplemented by on-site verification and measurement of:

- Spatial characteristics: Room dimension and layout, environmental control systems and constructional element thicknesses.
- Building envelope properties: Optical and thermophysical properties and fenestration parameters (U-values of interior and exterior walls and windows etc.).
- Environmental Control systems (Mechanical and Electrical) Systems: Heating, ventilation, and air-conditioning (HVAC) systems.

Simultaneously, outdoor climatic conditions are obtained from meteorological data and on-site reference measurements to establish contextual boundary conditions.

These factors should be systematically documented because they directly influence thermal comfort assessments. In parallel, outdoor environmental conditions are determined using meteorological data, and measurements.

Objective (Measurements) Method for Thermal Comfort Assessment

Thermal comfort is influenced by both objective and subjective parameters. Subjective parameters, which pertain to the individual characteristics of the human body, therefore vary from person to person. Consequently, thermal comfort assessments are typically based on objective parameters, which can be categorized into personal and environmental factors.

- Personal Thermal Comfort Factors: It is suggested that, clothing insulation (clo) is periodically updated to reflect seasonal variations. Determining instantaneous clothing insulation levels by surveys and entering them into the calculation of PMV produces more accurate assessments (Zoroğlu and Gedik, 2022). Activity levels are determined by observing general student behaviors and aligning them with these standards-based values (Zhang et al., 2020).
- Environmental Thermal Comfort Factors: Air temperature, mean radiant temperature, relative humidity, and air velocity are measured continuously and periodically.
- Thermal Comfort Indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are calculated using measured environmental data and personal parameters obtained from standards and surveys.

The objective methodology is aligned with ISO 7730 and ASHRAE Standard 55, ensuring compliance with internationally recognized protocols. Measurement points are selected to represent critical locations within the room, particularly areas close to windows or other potential dis-

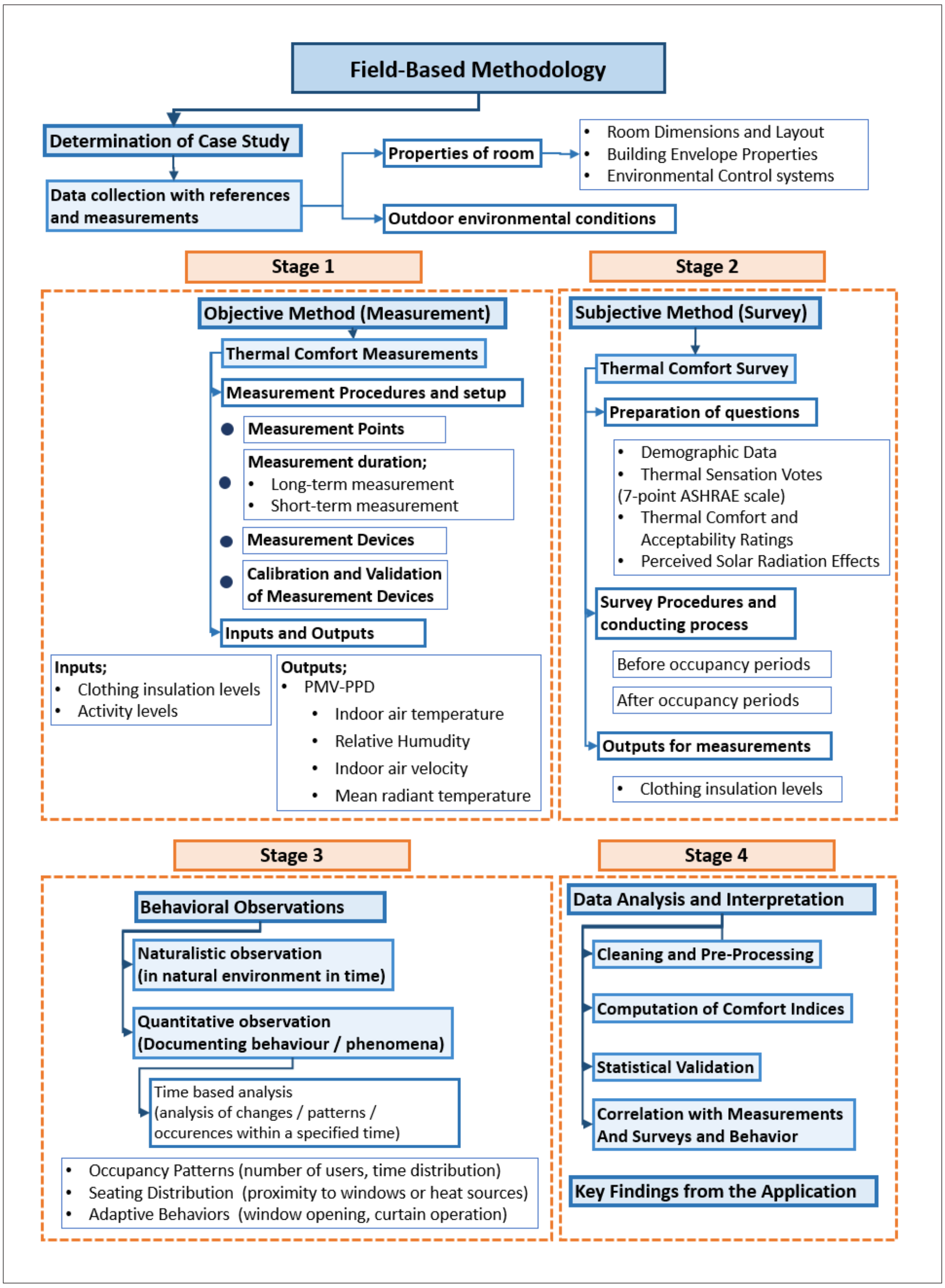


Figure 1. The field-based methodology for thermal comfort evaluation.

comfort zones, and are compared with reference points away from these zones. As suggsted relevant standards, air temperature and air velocity are measured at 0.1 m, 0.6 m, and 1.1 m heights, while humidity and mean radiant temperature are measured at 0.6 m to reflect seated occupant conditions.

Indoor thermal comfort measurements are conducted using calibrated thermal comfort measurement devices (e.g., Delta Ohm HD 32.3A, Testo 480), capable of calculating PMV/PPD. Long-Term measurements are performed with permanently installed devices, enabling continuous monitoring over representative periods. Short-Term measurements are conducted at selected intervals to capture real-time variations and transient conditions.

Measurement methodology of this study suggests that ensuring data integrity, so protective enclosures and uninterruptible power supplies (UPS) are used to prevent data loss and safeguard equipment from environmental disturbances.

Verification of thermal comfort measurement devices;

- Determination the relationship between devices: Comparison of measurement device results with each other (fixed measurements in a laboratory environment)
- Determination the protective enclosures effect: Comparison of devices within and without protective enclosures in real-word conditions
- Prior to field installation, all devices undergo laboratory calibration and inter-device comparison. Reliability is quantified using Mean Bias Error (MBE) and coefficient of determination (R^2) for key parameters (like air temperature, globe temperature, PMV). The methodology requires that MBE values remain within the ±10% acceptability range specified by ASHRAE Standard 14, so that measurements remain consistent across rooms. Additionally, R^2 values close to 1 show strong consistency between measurements.

Subjective (Survey) Method for Thermal Comfort Assessment

Thermal comfort surveys were administered before and after lesson, in accordance with ISO 10551:2019. Using a standards-based questionnaire not only enhances comparability across studies but also provides a consistent framework for interpreting subjective responses. The surveys applied in this study collect both subjective and objective parameters influencing thermal comfort (Figure 2):

- Demographic Data (age, gender, clothing insulation)
- Thermal Sensation Votes (7-point ASHRAE scale)
- Thermal Comfort and Acceptability Ratings
- Thermal preference and perceived impact on comprehension

This two-phase approach captures temporal variations in thermal perception and enables direct comparison between measured PMV and Actual Mean Vote (AMV). Clothing insulation (clo) values are collected through occupant surveys and periodically updated in PMV calculations to reflect seasonal changes.

Behavioral Observations for Thermal Comfort Assessment

Camera recordings and structured field notes are employed to record occupancy, seating distribution, and adaptive behaviors. These datasets are synchronized with measurement intervals, providing a holistic understanding of how

THERMAL COMFORT QUESTİONNAIRE
– BEFORE THE LESSON – Date:

Explanation: This survey has been prepared within the scope of a doctoral dissertation in the Building Physics Program at Yıldız Technical University. The aim is to evaluate the effects of perforated shading devices applied to classrooms on thermal comfort conditions and to assess occupants' satisfaction with the indoor environment according to international standards (ASHRAE 55, 2017; ISO 7730, 2005).

Personal Information

Gender: ☐ Female ☐ Male | Age: | Height (cm):
Weight (kg): | Employment status: ☐Retired ☐Employee ☐Student ☐Other…

Please indicate your education level: ☐ Graduate ☐ Undergraduate

1) Please select the clothing items you are currently wearing (closest options).

Footwear		**Lower Garments**		**Underclothing**	
Boots		Heavy trousers / Heavy skirt		Short socks	
Shoes		Trousers / Skirt		Thin long socks	
Sandals		Shorts / Light skirt		Thick long socks	
Upper Garments		**Outer Garments**		**Undershirt (Vest)**	
Sleeveless shirt		Cardigan / Jacket		Briefs	
Short-sleeved shirt		Waistcoat			
Long-sleeved sweatshirt		Overcoat			
Sweater					

Dress: (Sleeveless T-shirt/Short-sleeved T-shirt/ Long-sleeved T-shirt) + (Skirt)

Thermal Comfort Assessment

2) Please indicate your thermal sensation (7-point ASHRAE/ISO thermal sensation scale).
-3☐ Cold (-3) -2☐ Cool (-2) -1☐ Slightly cool (-1) 0☐ Neutral (0) +1☐ Slightly warm (+1) +2☐ Warm (+2) +3☐ Hot (+3)

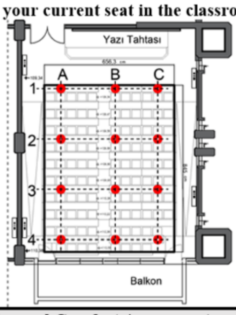
3) How do you evaluate the current thermal environment?
Extremely comfortable ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Extremely uncomfortable

4) How would you personally evaluate the acceptability of the current thermal environment?
Clearly acceptable ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7Clearly unacceptable

THERMAL COMFORT QUESTİONNAIRE
– AFTER THE LESSON – Date:

Personal Information

5) Please mark the location closest to your current seat in the classroom:



Thermal Comfort Assessment

6) Please indicate your thermal sensation (7-point ASHRAE/ISO thermal sensation scale).
-3☐ Cold (-3) -2☐ Cool (-2) -1☐ Slightly cool (-1) 0☐ Neutral (0) +1☐ Slightly warm (+1) +2☐ Warm (+2) +3☐ Hot (+3)

7) How do you evaluate the current thermal environment?
Extremely comfortable ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Extremely uncomfortable

8) How would you personally evaluate the acceptability of the current thermal environment?
Clearly acceptable ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 Clearly unacceptable

9) How would you prefer the thermal environment to be?
Much warmer ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐7 Much cooler

10) How does the classroom's thermal environment affect your comprehension and concentration?
Extremely positive ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐7 Extremely negative

Figure 2. Thermal comfort survey (questions) conducted before and after occupancy periods.

occupant actions interact with thermal comfort conditions. Observations include:

- Occupancy (number and positions of users, time distribution)
- Seating Distribution (proximity to windows or heat sources)
- Adaptive Behaviors (window opening, curtain operation)

Data Analysis and Interpretation

The final step of the methodology involves a combined evaluation of measurements, surveys, and behavioral observations. PMV values obtained from measurements are systematically compared with AMV derived from surveys, allowing the validation of measured results against occupant perception. To ensure reliability, the methodology emphasizes the synchronized collection of measurements and surveys, allowing occupant perception to be directly linked to the recorded indoor thermal comfort conditions. Behavioral data, including occupancy and window/curtain operation, are synchronized with measurement periods to contextualize variations in thermal comfort conditions.

The methodology prescribes a structured approach to data analysis:

- Data pre-processing: Removal of incomplete or erroneous readings.
- Computation of Comfort Indices: Calculation of PMV, AMV and relevant indices.
- Statistical Validation: Inter-device and inter-room comparison using MBE, R^2, and regression analyses, relationship between classrooms etc.
- Correlation with Measurements and Surveys and Behavior: Linking measured indices with AMV, APD, and behavioral patterns and identifying localized discomfort and validate model predictions.

This methodology provides a reliable and generalizable framework for thermal comfort evaluation, while the integrated analysis ensures a detailed assessment of room performance, orientation effects, and the identification of spatial discomfort.

APPLICATION OF THE METHODOLOGY

Following the development of the methodology, it was systematically implemented in three amphitheater-style classrooms at Yıldız Technical University's Beşiktaş Campus (B-501, B-502, B-503), each characterized by high window-to-wall ratios and distinct façade orientations (south, southeast, southwest). The aim was to demonstrate the reproducibility of the method, identify spatial discomfort zones, and validate the integration of objective, subjective, and behavioral data under real word conditions.

The selection process prioritized classrooms with high solar exposure and expected non-uniform thermal comfort conditions. Architectural drawings were reviewed to determine room dimensions, seating arrangements, and façade configurations, which were subsequently verified through on-site measurements.

The amphitheater form of classrooms (Figure 3) and thermophysical principles—where heated air rises and accumulates near windows—further intensified discomfort in façade-adjacent areas, particularly during periods of occupancy. The physical characteristics of the classrooms are summarized in Table 1 and Table 2 presents the window-to-wall ratios (WWR).

Building envelope properties (section layers, materials, and U-values) were determined using the TESTO 635 humidi-

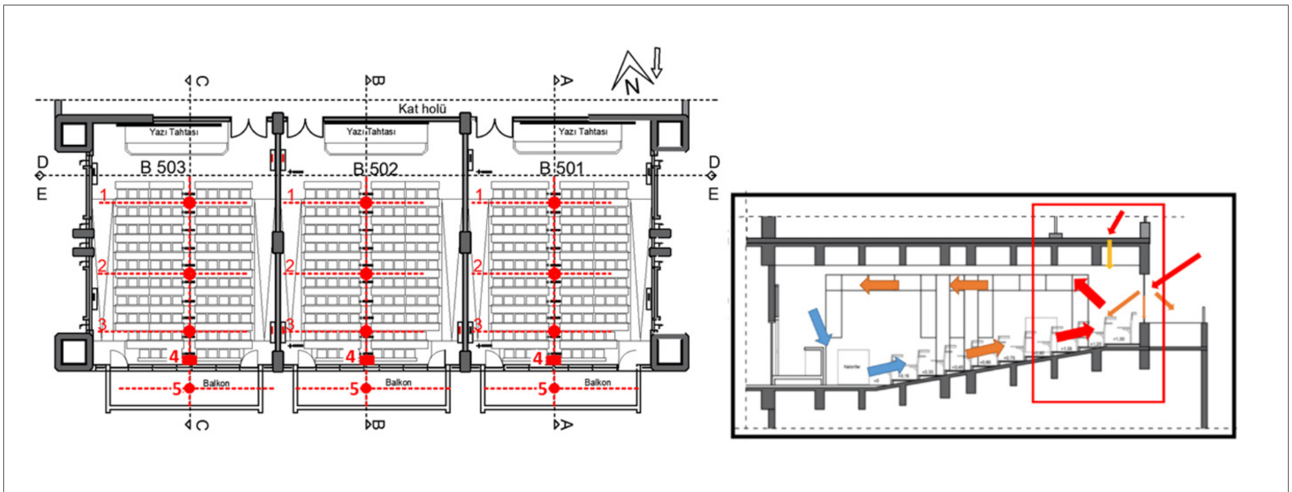


Figure 3. Thermal Comfort Measurement Points in Classrooms (Points 1, 2, and 3 for short-term measurements, and Point 4 for fixed measurements, Point 5 for outdoor weather conditions measurement) and Sections of Classroom B-501.

Table 1. Physical characteristics of classrooms.

Classrooms	Direction of classroom	Dimensions (amphitheater)	Heating system and number of Radiator	Capacity (person)
B 501	South-East	11.76×9.08×(2.7-3.80)	Gas central heating systems, Cast iron radiator- 4 radiators	109
B 502	South	11.76×8.90×(2.7-3.80)	Gas central heating systems, Cast iron radiator- 3 radiators	109
B 503	South-West	11.76×9.08×(2.7-3.80)	Gas central heating systems, Cast iron radiator- 4 radiators	109

Table 2. Current transparency ratios of rooms.

Room	Direction of Classroom	Capacity (person)	Dimension of Classroom	Direction of transparent component	Transparency Ratio (WWR – Window to Wall Ratio)		
					East	South	West
B 501	South-East	109	11.76x9.08×(2.7-3.80)	**South and East**	11.5%	60%	-
B502	South	109	11.76×8.90×(2.7-3.80)	**South**	-	60%	-
B503	South-West	109	11.76×9.08×(2.7-3.80)	**South and West**	-	60%	11.5%

ty and architectural documentation. Classrooms equipped with mechanical heating and natural ventilation were intentionally selected to allow diverse evaluations of thermal comfort. Table 3 details the building envelope section layers and associated U-values derived from field measurements and project drawings.

The methodology was tested between 3 and 19 November through long-term measurements, while short-term measurements and occupant surveys were simultaneously conducted on 17 November. Outdoor climatic conditions were recorded at a designated reference point 5 (Figure 3), and the results are presented in Table 4.

Application of Objective (Measurements) Method

The first stage of the application involved defining measurement points within the selected rooms. These points were chosen strategically to capture the spatial variability of thermal comfort conditions, with one point always located near the south-facing window to record the influence of solar exposure. Four points per classroom were selected, including points near the south-facing windows and reference points farther away, to capture spatial gradients. In each classroom, three points were determined for short-term measurements, while one fixed point was chosen for continuous long-term monitoring (4. point) (Figure 3).

The Delta Ohm HD 32.3A Microclimate Analyzer and Testo 480 were employed to record air temperature, mean radiant temperature, relative humidity, and air velocity. Clothing insulation and activity level (Table 5) were integrated into the devices, enabling calculation of PMV and PPD. Thermal comfort assessment was conducted in accordance with ISO 7730 and ASHRAE Standard 55.

Following the selection of measurement points, measurement devices and periods, three Delta Ohm HD 32.3A microclimate analyzers were permanently installed near the windows to collect long-term data, while a fourth device was used to perform short-term measurements at other points. Protective enclosures and UPS systems (Figure 4) were used to safeguard devices and prevent data loss due to power fluctuations.

Prior to field study, all devices underwent laboratory calibration and inter-device comparison. The statistical analysis revealed Mean Bias Error (MBE) values of +0.034 between Device 1 and 2, +0.064 between Device 1 and 3, and +0.030 between Device 2 and 3, all of which remained within the acceptable ±10% threshold. The corresponding coefficients of determination (R^2=0.959, 0.919, and 0.916, respectively) indicated strong correlations across devices. These results confirmed the reliability of the measurement devices (Figure 5) and validated the data quality and comparability across classrooms.

The effect of protective enclosures was evaluated under real-word conditions. Verification results demonstrated that the enclosures did not significantly affect measurement accuracy, with MBE in PMV, and PPD remaining within the ±10% range (Table 6). These outcomes validated the suitability of the experimental setup for long-term monitoring and confirmed that the collected data can be considered reliable.

Application of Subjective (Surveys) Method

The thermal comfort surveys were administered immediately before and after lessons, in accordance with ISO 10551:2019, in order to capture temporal changes in thermal perception.

Table 3. Building envelope section layers according to architectural drawings and U values from measurements.

Building envelope Components	Measurement U-Value (W/m2K)	Section Layers (Project)	
		Material	Thickness (m)
Exterior Wall	0.387	Plaster	0.02
		Heraklith	0.03
		Exposed Concrete	0.15
Internal Wall	0.732	Perforated Particleboard	0.025
		Exposed Concrete	0.05
		Bakelite Glass Wool	0.05
		Perforated Particleboard	0.025
Ceiling-Floor	-	Rubber Floor Covering	0.05
		Alum	0.025
		Leveling Concrete	0.04
		Reinforced Concrete Floor	0.1
Terrace Roof	-	Tile Mosaic	0.025
		Mortar	0.025
		Ruberoid and Water Insulation(3 layers)	-
		Polyurethane heat insulation	0.05
		Vapor Insulation	-
		Slope concrete	0.03 – 0.24
		Reinforced Concrete Floor	0.1
Window	1.847	-	-
Door	1.5	-	-

In addition to demographic data such as age, gender, and clothing insulation levels, the questionnaires included thermal sensation votes with seven-point scale, thermal comfort and acceptability ratings, and thermal preference, and perceived influence on comprehension and concentration. This design enabled a direct comparison between the measured PMV and the AMV derived from occupant responses. Surveys were conducted simultaneously with short-term measurements on 17 November 2021, involving 24 participants.

Application of Behavioral Observation

Behavioral observations were conducted through a camera recording system installed in each classroom (Figure 6; Figure 7). The recordings were analyzed to determine occupancy levels, seating distribution, and adaptive behaviors such as window and curtain operation. These observations were synchronized with the measurement periods, providing a comprehensive interpretation of occupant behavior in relation to thermal comfort conditions.

RESULTS

The systematic implementation of the proposed methodology enabled the identification of spatial thermal gradients, localized discomfort zones, and the correspondence between occupant perception and measured thermal indices.

Data Analysis, Validation and CrossRoom Comparison

The data analysis process was conducted in two distinct stages. The first stage comprised preliminary verification analyses carried out prior to field study, including device calibration, inter-device comparison, and the evaluation of protective enclosures. These assessments, presented in the methodology section, confirmed negligible differences between de-

Table 4. The outdoor climate conditions during short-term field study.

Date	Time	Mean Radiant Temperature (C°)	Air Temperature (C°)	Relative Humidity, RH (%)	Air Velocity, Va (m/s)	Sky Condition
17.11.2021	14:17	20.7	18.8	45.2	0.53	Overcast

Table 5. Field study measurement Parameters.

Measurement points	Measurement Height	Measurement type-time and interval	Activity Level	Clothing insulation level
4 points for each classroom	0.6 meters	According to Time - Short-term (15 min) and long-term measurements Both: 30 sec. intervals	1.2 met	Be determine depending on periods (0.8 clo, in this field study)

Note: Devices were acclimatized for 15 minutes before measurements.

Table 6. The mean values and standard deviations of the measurement results obtained under both protected and unprotected conditions for the 1. device.

		Tg (C°)	Ta (C°)	RH (%)	Va (m/s)	PMV	PPD (%)
Protected	Mean	34.20	33.41	46.50	0.009	2.83	97.99
	Std. Dev.	0.34	0.15	0.52	0.01	0.08	0.80
Unprotected	Mean	34.74	33.76	45.93	0.018	2.96	98.90
	Std. Dev.	0.31	0.21	0.39	0.015	0.08	0.36
MBE		-1.55	-1.04	1.24	-50.0	-4.39	-0.92

Tg: Mean radiant temperature, Ta: Air temperature, RH: Relative humidity, Va: Air velocity

vices and demonstrated that Mean Bias Error (MBE) values for PMV remained within the ±10% acceptability threshold, thereby ensuring that subsequent measurements were both valid and comparable across classrooms.

The second stage focused on the systematic integration and interpretation of field data. This stage analiyzed and combined measurements, surveys, and behavioral observations to capture spatial and temporal variations in thermal comfort conditions.

Measurement Results

Field measurements revealed clear spatial and temporal variations in thermal comfort conditions across the three classrooms. Short-term measurements (Figure 8) indicated pronounced thermal gradients, with PMV values at window-adjacent points exceeding +0.5 and globe temperatures more than 2 °C higher than those recorded at central points.

The implementation of the methodology successfully identified localized discomfort zones near the south-facing façades where PMV values exceeded the recommended comfort thresholds (Figure 8). These findings confirm the dominant influence of direct solar radiation on local thermal comfort conditions. Under overcast sky conditions (17 November 2021), temperature differences between façade-adjacent and central points were smaller yet still measurable, indicating that thermal asymmetry persists even in the absence of direct sun. Furthermore, in Classroom B-502, although the air temperature and MRT at

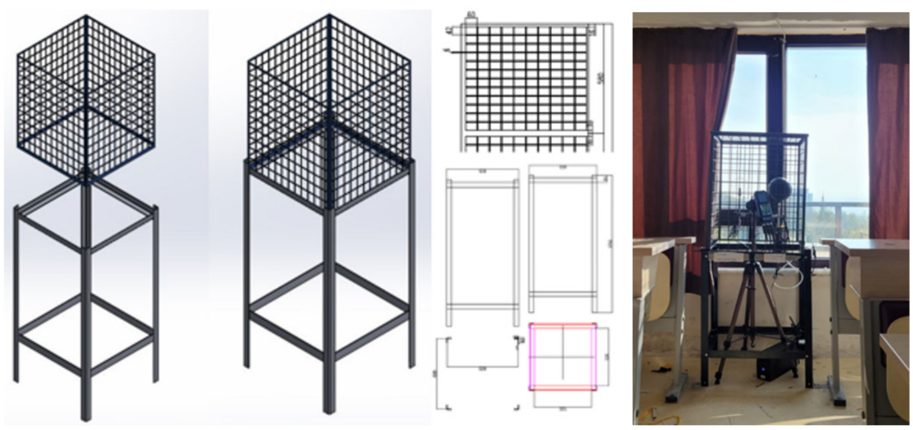


Figure 4. Protective enclosures for thermal comfort measurement devices.

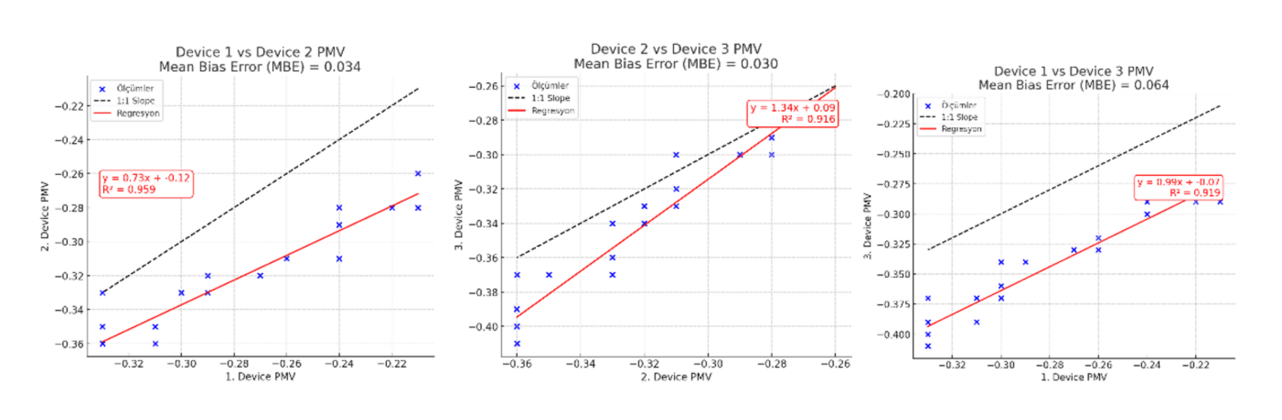


Figure 5. Verification of measurement devices (MBE and coefficient of determination (R^2) for PMV) (237 data for each device and indices-1 hour and 30 sec. intervals).

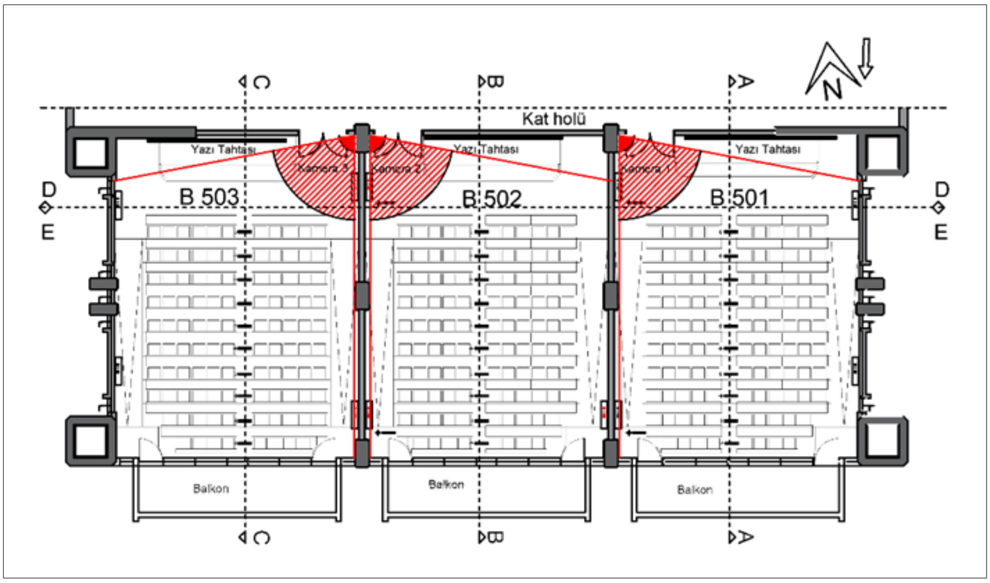


Figure 6. Camera Positions and Fields of View (Red-shaded areas indicate non-visible zones).

Point 1 were relatively higher than other points, the PMV value was observed to be lower than at the other points due to higher air velocity and lower relative humidity at this point.

Long-term monitoring was conducted between 3 and 19 November 2021, with measurements taken at 09:00, 11:00, 13:00, 15:00, and 17:00 to represent full-day conditions. The results demonstrated a consistent pattern of afternoon overheating across all classrooms (Figure 9). PMV values peaked between 13:00 and 15:00, with the most pronounced overheating observed in Classroom B-503, where PMV frequently exceeded +0.7. Classroom B-501 exhibited more pronounced morning gradients due to its east-facing façade. Relative humidity remained within the 40–60% range recommended by ASHRAE 55, and air velocity stayed below 0.05 m/s, indicating negligible effects

Figure 7. Photograph Captured from Classrooms Cameras (respectively B-501, B-502 and B-503) on 15.06.2021 at 10:00 AM.

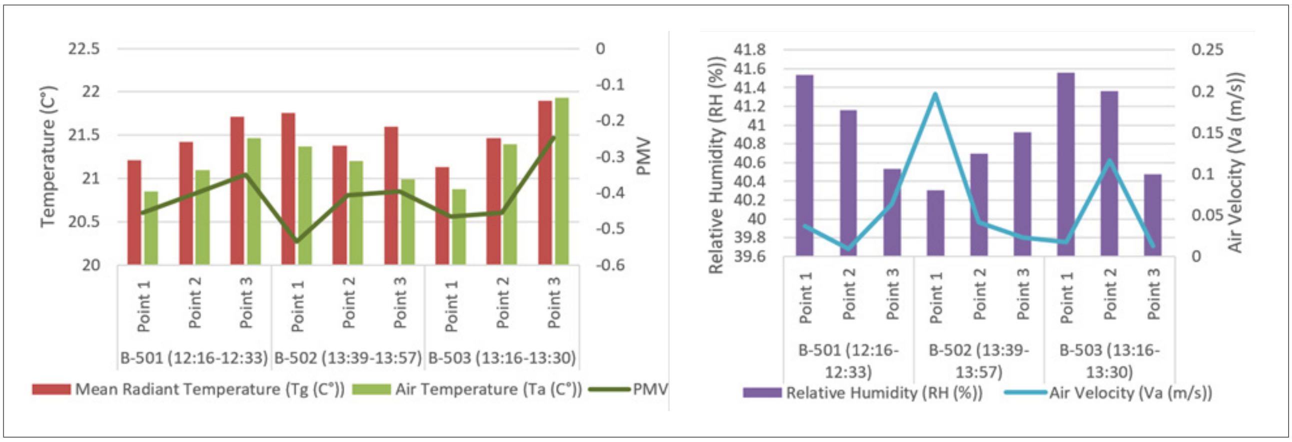


Figure 8. Short-term Measurement Results on November 17, 2021 (Mean Radiant Temperature, Air Temperature, Relative Humidity, Air velocity, and PMV).

Figure 9. Long-term Measurement Results for Classroom B-501, B-502 and B-503 from November 3–19, 2021 (Mean Radiant Temperature, Air Temperature and PMV).

of natural ventilation. These results demonstrate that solar heat gains and temperature rise, rather than humidity or air movement, were the primary drivers of discomfort.

Survey Results

The thermal comfort surveys corroborated the measurement data and provided valuable insight into occupants' thermal perception. Survey results from 17 November 2021 (Table 7) show that before lesson, 50% of respondents reported "slightly warm" and 16.7% "warm," while 25% selected "neutral". Following lessons, the proportion of "slightly warm" votes decreased to 45.8%, with an increase in neutral responses (25% to 45.8%), suggesting partial adaptation and convergence toward neutrality. Despite these adaptations, more than 70% of of participants consistently rated the thermal environment as acceptable or better, although dissatisfaction was concentrated among students seated near the façades.

Thermal comfort acceptability (question 4 and 8) ratings improved after lesson, while thermal preference (question 9) responses indicated that nearly half of the students (45.8%) preferred no change, confirming that conditions were close

Table 7. Results of the thermal comfort survey conducted in classrooms on november 17, 2021 (Results are presented as percentage values (%)).

Before Lesson					.		
Question 2 (Thermal Sensation)	Hot (+3)	Warm (+2)	Slightly Warm (+1)	Neutral (± 0)	Slightly Cool (-1)	Cool (-2)	Cold (-3)
		4.2	16.7	50	25	4.2	
Question 3	Extremely Uncomfortable-1	2	3	4	5	6	Extremely Comfortable-7
			16.7	29.2	25	20.8	8.3
Question 4	Clearly Unacceptable-1	2	3	4	5	6	Clearly Acceptable-7
			12.5	16.7	16.7	33.3	20.8
After Lesson					.		
Question 6 (Thermal Sensation)	Hot (+3)	Warm (+2)	Slightly Warm (+1)	Neutral (± 0)	Slightly Cool (-1)	Cool (-2)	Cold (-3)
		4.2	16.7	45.8	25	8.3	
Question 7	Extremely Uncomfortable-1	2	3	4	5	6	Extremely Comfortable-7
			16.7	25	33.3	25	
Question 8	Clearly Unacceptable-1	2	3	4	5	6	Clearly Acceptable-7
		4.3	13	13	30.4	30.4	8.7
Question 9	Much Cooler-1	2	3	4	5	6	Much Warmer-7
		4.2	12.5	45.8	29.2	4.2	4.2
Question 10 (Comprehension and concentration)	Extremely Negative-1	2	3	4	5	6	Extremely Positive-7
			29.2	20.8	29.2	16.7	4.2

to the acceptable limit. Comprehension and concentration scores remained largely neutral to positive, indicating no significant cognitive impact of the thermal environment.

Students' thermal sensation votes before and after the lesson showed a moderate-to-strong correlation (R^2=0.6462), indicating stable thermal perception throughout the lesson. The regression line (y=0.8657x + 0.4483) suggests a slight convergence toward neutral sensations, which may reflect partial thermal adaptation during occupancy. Overall, the results indicate that the time elapsed during the lecture did not significantly affect thermal comfort.

Figure 10 illustrates the variation of AMV with respect to seating location before and after the lesson. A positive trend was observed in both cases, indicating that students seated closer to the window reported higher thermal sensation votes than those seated farther away. The relationship was slightly stronger before the lesson ($R^2 \approx 0.32$) compared to after the lesson ($R^2 \approx 0.26$), suggesting a modest adaptive effect over time, as occupants gradually became accustomed to the thermal environment.

These findings confirm the presence of spatial thermal gradients within the classroom and highlight the sensitivity of occupant thermal perception to seating position, with façade-adjacent areas consistently associated with warmer sensations.

Results of Behavioral Observations

Camera recordings of occupancy provided additional context for interpreting the measurement and survey data. According to analysis of camera recordings (Figure 11), it can be concluded that students tended to avoid seating near the façades indicating behavioral adaptation in response to localized discomfort. Curtains were generally left partially open during morning and midday periods, which allowed solar penetration and contributed to elevated mean radiant temperatures, especially near south facade. The analysis further indicated that windows were generally operated intermittently, leading to additional solar gains and increased PMV values near the façades.

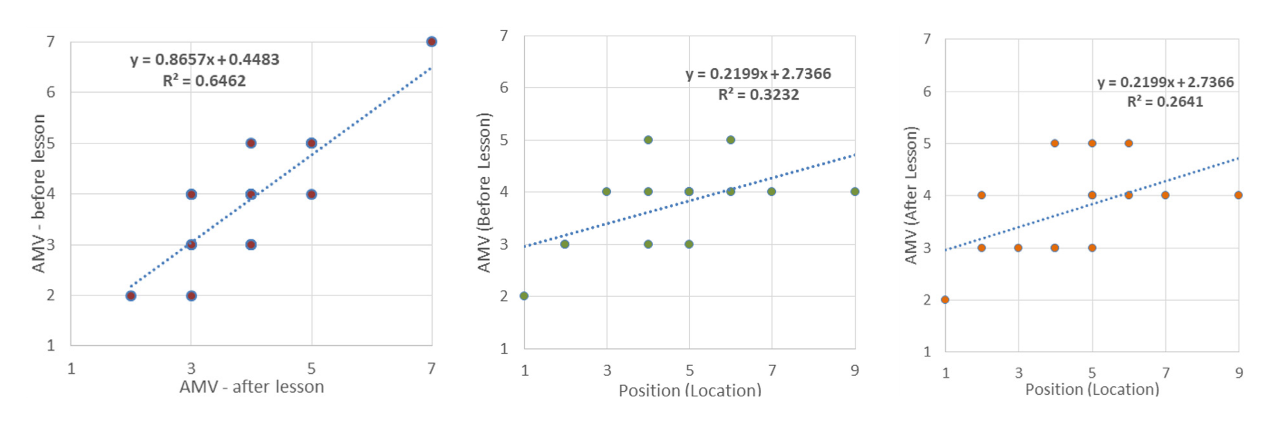


Figure 10. The variation of AMV before and after the lesson and relation with seating location.

Synthesis of Findings

Inter-room comparisons were conducted by statistically analyzing PMV data collected between 3–19 November, employing Mean Bias Error (MBE) and the coefficient of determination (R^2) as key performance indicators. The analysis revealed that the strongest agreement was observed between B-502 and B-501 (MBE ≈ –0.009; $R^2 \approx 0.65$), reflecting the generally uniform thermal behavior of these two south-oriented classrooms despite B-501's southeast façade exposure. The relationship between B-503 (southwest-oriented) and B-502 (MBE ≈ –0.085; $R^2 \approx 0.55$) exhibited moderate agreement, whereas the weakest correlation was found between B-503 and B-501 (MBE ≈ –0.094; $R^2 \approx 0.52$), attributable to the combined effects of B-501's morning solar gains from the southeast and B-503's afternoon overheating due to southwest exposure.

These orientation effects resulted in distinct diurnal PMV: B-501 exhibited pronounced morning gradients, B-503 experienced elevated afternoon PMV peaks, while B-502, being purely south-facing, displayed a more balanced thermal profile across the day. Despite the differences in correlation strength, all MBE values remained well within the ±10% acceptability thresholds, indicating spatial/temporal effects. This outcome highlights the methodology's sensitivity to façade orientation effects and confirms its capacity to capture both temporal and spatial non-uniformities in thermal comfort performance. Consequently, the developed approach provides a reliable basis for informing evidence-based retrofit strategies and simulation-driven optimization (Figure 12).

Figure 13 illustrates the relationship between PMV and three key behavioral parameters: Curtain operation, window operation, and occupancy. Curtain operation exhibited a negligible correlation with PMV ($R^2 \approx 0.002$), confirming that shading devices were largely kept in a fixed position regardless of thermal comfort conditions. On average, curtains remained closed 47.9% of the time, indicating that solar control was predominantly maintained in a closed state throughout the measurement period.

Window operation showed a weak but positive correlation with PMV ($R^2 \approx 0.06$), suggesting a modest tendency to open windows under warmer conditions. However, the mean window opening rate was only 16.7%, demonstrating that natural ventilation was seldom adopted as an adaptive measure. Occupancy levels displayed only a very weak relationship with PMV ($R^2 \approx 0.01$), indicating that fluctuations in student numbers contributed minimally to thermal variability.

Collectively, these findings reveal a behavioral pattern characterized by limited active adaptation, with solar control dominated by a consistently closed curtain state and window operation being infrequent.

Table 8 compares AMV and PMV values. B-503 exhibited the highest AMV (4.30) reflecting slightly warm sensations, but alongside a nearly neutral PMV (–0.04), consistent with its southwest exposure. B-502 presented the lowest PMV (–0.46), consistent with cooler indoor conditions, while B-501 remained near neutral but slightly cooler (AMV 3.5; PMV –0.27). The overall alignment between AMV and PMV indicates consistency between measured and perceived comfort, with differences explained by orientation-driven solar gains.

The integrated dataset, combining objective measurements, occupant surveys, and behavioral observations, provided a comprehensive assessment of thermal comfort that captured both physical and experiential dimensions. Localized overheating near south-facing façades was consistently detected, and occupants seated near the windows reported greater thermal dissatisfaction. These findings were corroborated by measurement and survey data, which indicated higher levels of thermal dissatisfaction and reduced lesson comprehension near the windows. Limited curtain and window use were insufficient to mitigate discomfort, resulting in persistent PMV levels above recommended comfort thresholds. The strong correlation between measured and perceived comfort indices validated the methodology and confirmed its capacity to accurately diagnose thermal comfort conditions.

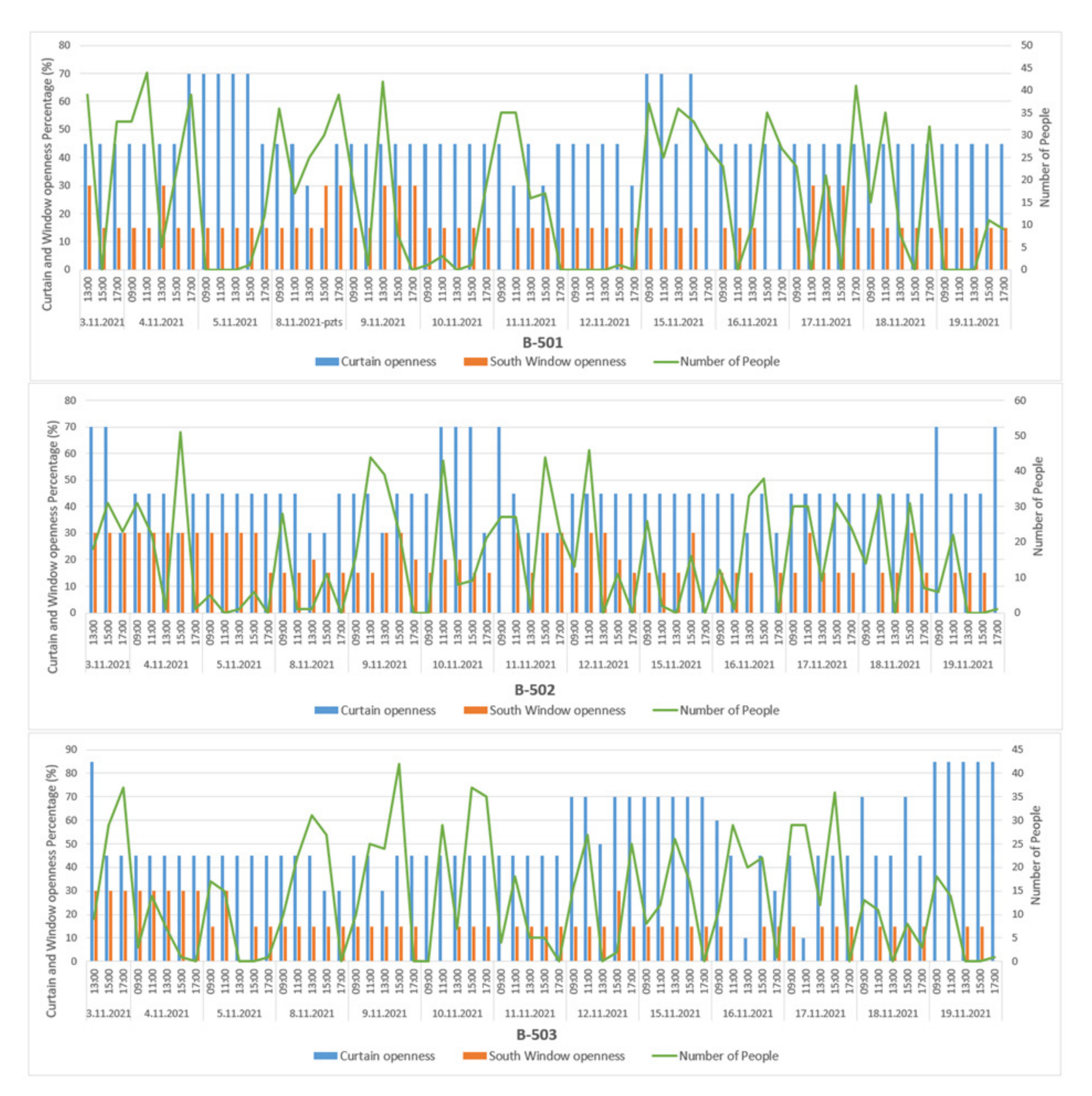


Figure 11. Occupancy (number of people), curtain (curtain openness percentage) and window (window openness percentage) operation of Classroom B-501, B-502 and B-503 from 8:00 AM to 5:00 PM between November 3–19, 2021 (except weekends).

DISCUSSION

The findings of this study highlight the interaction between measured thermal comfort conditions, occupant perception, and behavioral responses in university classrooms. PMV values near the south-facing façades exceeded comfort thresholds during afternoon hours, confirming the dominant effect of solar gains. The amphitheater configuration, with extensive south-facing glazing and tiered seating, intensified discomfort for students seated near the windows, while convective air movement contributed to localized heat accumulation. Despite these asymmetries, converted AMV scores were broadly consistent with PMV predictions, suggesting that the model provided a reasonable estimation of perceived comfort. Minor deviations near the façades are consistent with previous findings that predictive models may not fully capture adaptive tolerance in mixed-mode environments (de Dear & Brager, 1998; Humphreys & Nicol, 2002). The integration of subjective surveys allowed PMV results to

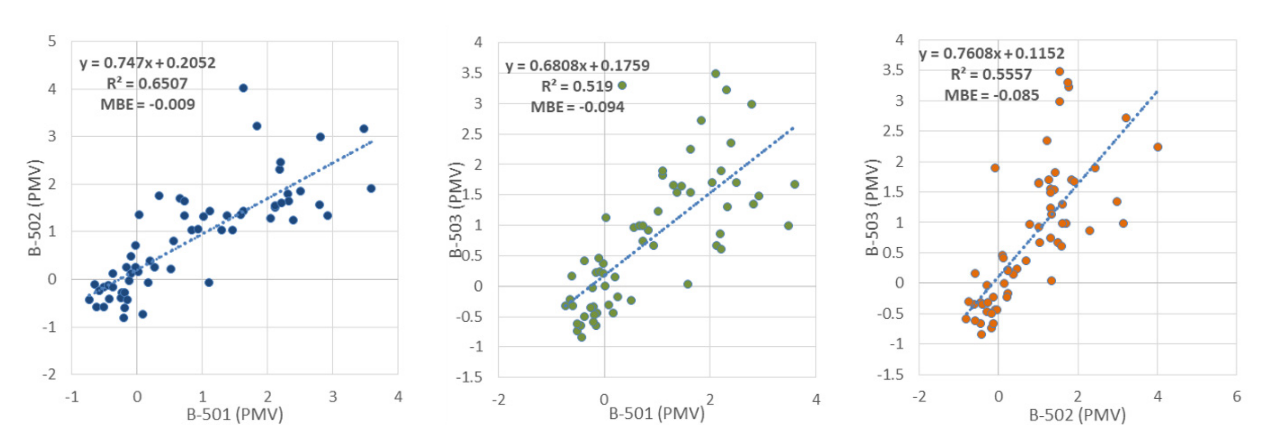


Figure 12. Comparison of classrooms (3–19 November).

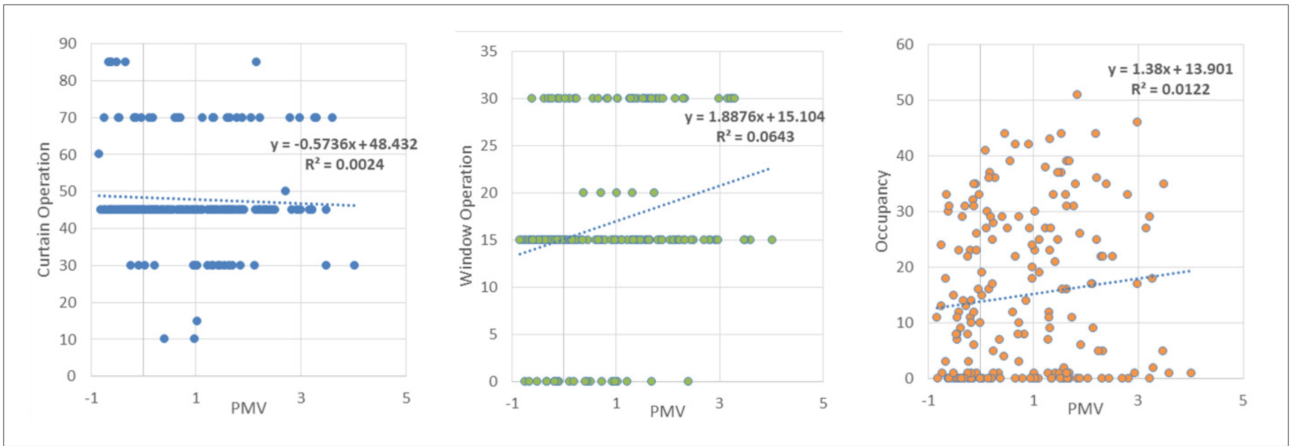


Figure 13. The comparison the relationship between PMV and curtain operation, window operation, and occupancy respectively.

be directly compared with occupant votes, thereby enhancing external validity. The results is consistent with the adaptive comfort framework proposed by Nicol and Humphreys (2002), which demonstrates that acceptable comfort ranges expand with outdoor climatic conditions, particularly in warm climates.

Table 8. Comparison of AMV and PMV.

	B-501	B-502	B-503
AMV			
Mean	3.50	3.70	4.30
Std.dev.	0.50	0.90	1.15
AMV (Converted)			
Mean	−0.5	−0.3	0.30
PMV			
Mean	−0.27	−0.46	−0.04
Std.dev.	0.26	0.34	0.29

It should be noted that although long-term measurements were conducted to evaluate thermal comfort across working place, surveys were applied on a single day at the same time with short-term measurements under overcast sky conditions, which limits the representativeness of the findings. As emphasized by Fabi et al. (2012), short-term or condition-specific studies may not capture seasonal variability, highlighting the need for longer-term studies. Therefore, it is recommended that future survey studies adopt seasonally distributed applications to better capture occupant variability.

Behavioral observations revealed limited adaptation: Curtains were kept closed nearly 48% of the time and windows were opened in ≈ 17% of cases, resulting in persistent overheating near façades. These results support Schweiker and Wagner (2016), who reported that occupants often underutilize available control opportunities, leaving them exposed to thermal discomfort. Furthermore, the observed avoidance of window-adjacent seats is consistent with Yan et al. (2015), who emphasized that spatial discomfort influences seating preferences and adaptive behavior.

Even under overcast conditions, façade transparency caused thermal effects, confirming the importance of solar control and occupant-centric solutions like automated shading and natural ventilation (Tzempelikos & Athienitis, 2007). According to findings, it is suggested that retrofit measures such as external shading, selective glazing, and adaptive interior systems are recommended to mitigate solar gains, particularly in southeast- and southwest-facing classrooms.

In summary, while predictive models such as PMV align reasonably well with occupant perception, their limitations in capturing adaptive tolerance and transient effects necessitate field-based validation. The integration of surveys and behavioral data strengthens validity, while the identified methodological constraints highlight the importance of extended monitoring and cross-seasonal applications.

CONCLUSION

This study developed and validated a field-based methodology for assessing thermal comfort in university classrooms with high window-to-wall ratios and strong solar exposure. By integrating objective measurements, occupant surveys, and behavioral observations, the approach provided a detailed assessment of thermal comfort conditions under real environmental conditions. Its application in three classrooms with different façade orientations confirmed its ability to capture spatial differences and the relationship between predicted and perceived comfort.

The results showed that southeast and southwest-facing classrooms experienced the highest thermal stress, while the south-facing classroom exhibited more uniform conditions. Behavioral observations revealed limited adaptation, with curtains largely closed and windows rarely used, indicating reliance on passive or automated systems.

While limited to three classrooms, the findings demonstrate the method's reproducibility. This study demonstrates the value of a field-based, standards-compliant methodology for assessing thermal comfort under real-word conditions. The close correspondence between AMV and PMV supports the validity of the approach, and most PMV values were within acceptable comfort ranges.

Future research should extend this methodology to different building types, climates, and cultural contexts; incorporate longer-term monitoring studies across multiple seasons; and integrate additional indoor environmental parameters such as daylight quality, acoustics, and indoor air quality. Expanding survey questions to capture transient perceptions, thermal perceptions, and cognitive performance would also deepen understanding of comfort dynamics. Overall, this study demonstrates the potential of a standards-compliant, field-based methodology to bridge the gap between predicted indices and lived experience.

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