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Thermal Comfort Performance of Existing Perforated Solar Screens Across Different Façade Orientations: A Field-Based Study

* Fatma Zoroğlu[1], Elif Çağla Başdoğan[2], Aylin Yalnız[3], Doğa Öngener[4], Yağmur Haydaroğlu[5], Ceren Zoroğlu[6]

Department of Architecture, Faculty of Architecture and Design, Adana Alparslan Türkeş Science and Technology University, Adana, Türkiye[1]

Department of Architecture, Faculty of Architecture, Yıldız Technical University, Istanbul, Türkiye[2]

Independent Researcher, Türkiye[3, 4, 5]

Department of Architecture, Faculty of Architecture, Erciyes University, Kayseri, Türkiye[6]

E-mail[1]: fzoroglu@atu.edu.tr, E-mail[2]: elifcaglabasdogan@gmail.com, E-mail[3]: aylinyalnaz@gmail.com, E-mail[4]: dogaaongener@gmail.com, E-mail[5]: yagmurhaydaroglu03@gmail.com, E-mail[6]: zorogluceren13@gmail.com

ABSTRACT

This study investigates the thermal comfort performance of perforated solar screens in educational and office buildings on university campuses, focusing on façade orientation. Although the performance of shading devices has been widely investigated through simulation-based studies, field-based evidence evaluating their thermal comfort performance under real operating conditions remains limited. To address this gap, classrooms and offices oriented along north–south and east–west axes were examined under real operating conditions. Field-based on-site measurements were conducted at representative points, defined according to the seating layout in classrooms and as window-adjacent and interior zones in offices. Thermal comfort was assessed using the Predicted Mean Vote (PMV), derived from on-site measurements, and compared with comfort ranges defined by ISO 7730 and ASHRAE 55. The results indicate orientation-related variations in PMV, particularly in south-oriented offices, where PMV values reached up to +1.16 at window-adjacent zones and frequently exceeded the comfort limits despite the presence of shading devices. In contrast, PMV values in north-oriented spaces generally remained within the recommended comfort range. In south-oriented classrooms, PMV values remained within acceptable limits but were biased toward warm conditions, with the observed conditions also reflecting active cooling and curtain use. Spatial PMV differences within classrooms ranged between 0.05 and 0.15, indicating differences in the spatial distribution of predicted thermal comfort conditions. These findings suggest that identical perforated solar screen configurations may not provide equivalent thermal comfort performance across different façade orientations. The originality of this study lies in its field-based evaluation of perforated solar screens under actual operating conditions. The findings emphasize the need for orientation-sensitive, climate-responsive shading design and provide empirical evidence that can support façade design decisions in educational buildings.

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Corresponding Author:
Fatma Zoroğlu
Department of Architecture, Faculty of Architecture and Design, Adana Alparslan Türkeş Science and Technology University, Adana, Türkiye
E-mail: fzoroglu@atu.edu.tr

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1. Introduction

Educational and office buildings located on university campuses stand out as spaces with high thermal comfort requirements due to their long occupancy periods, high user density, and functions that require sustained cognitive performance. Indoor environmental quality has been shown to have a significant impact on occupant comfort, health, and work performance, particularly in educational and office buildings where cognitive performance is essential (Wargocki & Wyon, 2017; Frontczak & Wargocki, 2011).

In such buildings, façade orientation, solar radiation, window-to-wall ratio (WWR), and the design of shading devices are among the key design parameters that directly and indirectly influence indoor environmental conditions. The building envelope functions as a physical and environmental separator between the indoor space and the outdoor environment and is defined as the primary building component that regulates heat, air, and moisture transfer between these two environments (Straube, 2017).

Façade orientation determines the amount, timing, and angle of solar radiation received by the building envelope. Therefore, identical or similar shading configurations may not result in equivalent thermal conditions on different façades. East and west façades are exposed to low-altitude solar radiation, which is difficult to control with fixed shading devices and may increase the risk of overheating. This is mainly due to the low solar altitude angles in the morning and afternoon, which allow direct solar radiation to penetrate deep into indoor spaces. In contrast, north façades receive predominantly diffuse sky radiation, while solar radiation on south façades occurs at higher angles and can be more effectively controlled using horizontal shading devices due to higher solar altitude angles at solar noon (Szokolay, 2014; Lechner, 2014). This orientation-dependent solar exposure creates differences not only in solar heat gains but also in indoor radiant conditions, particularly in perimeter zones close to glazed façades.

Since thermal comfort is strongly influenced by environmental parameters such as air temperature, mean radiant temperature, air velocity, and humidity, mean radiant temperature plays a critical role in thermal comfort evaluation (Olesen & Parsons, 2002). Solar gains transmitted through or absorbed by façade components may increase surface temperatures and consequently affect mean radiant temperature. Since PMV is sensitive to changes in mean radiant temperature, façade orientation and shading configuration may influence the spatial distribution of PMV values within a room. Accordingly, this study is based on a conceptual framework in which façade orientation affects solar exposure, solar exposure influences indoor radiant conditions, radiant conditions affect PMV distribution, and perforated solar screens may moderate this relationship depending on their geometry and façade-specific suitability.

Shading devices, which are considered within the scope of passive design strategies, play an important role in limiting excessive solar gains and balancing radiant heat loads in indoor environments. In addition to controlling solar radiation, shading devices influence indoor air temperature, mean radiant temperature, and overall thermal comfort by reducing solar heat gains and lowering surface temperatures exposed to direct solar radiation (Olgyay, 2015; Givoni, 1998). Since mean radiant temperature is a key parameter in the radiant heat exchange between the human body and surrounding surfaces and plays a central role in thermal comfort evaluation (Fanger, 1970; Olesen & Parsons, 2002; Guo et al., 2020; Tamrakar et al., 2023), shading devices can significantly improve indoor thermal conditions by reducing radiant heat gains. However, the effectiveness of shading devices depends not only on their presence but also on façade orientation, solar angles, and building geometry. In the literature, horizontal shading devices are generally considered more effective on south façades, whereas vertical shading devices are more suitable for east and west façades due to differences in solar path and façade incidence angles (Szokolay, 2014; Lechner, 2014). Although these orientation-based design principles are well established, less is known about how existing perforated solar screens perform in occupied buildings under actual operating conditions, where HVAC operation, curtain use, occupancy, and user behaviour may alter expected performance.

Previous studies on shading devices have primarily focused on energy and daylight performance, and many of these studies have been conducted using simulation tools. Studies addressing thermal comfort and real building conditions are comparatively limited (Kirimtat et al., 2016). Although simulation-based studies provide valuable insights during the design phase, field measurements are essential for validating simulation results and understanding actual occupant comfort conditions under real operating environments. Furthermore, field studies on thermal comfort have demonstrated that occupants adapt to their thermal environment, highlighting the importance of real building measurements in addition to simulation-based studies (de Dear & Brager, 1998; Nicol & Humphreys, 2002). As a result, discrepancies may occur between predicted shading performance and the thermal comfort conditions observed in real buildings.

This need is particularly relevant for perforated solar screens. Unlike conventional horizontal or vertical shading devices, perforated solar screens simultaneously influence solar transmission, daylight availability, outward visibility, façade permeability, and potentially ventilation. Their thermal performance is therefore not determined only by their presence but also by perforation characteristics, installation geometry, façade orientation, and operational context.

Existing studies on perforated solar screens have mainly addressed daylight availability, glare control, energy efficiency, and parametric optimization through simulation-based approaches. For example, Appelfeld et al. (2012) compared perforated shading screens with conventional shading systems through hourly building simulations, while Chi et al. (2017) optimized perforated solar screen configurations by integrating daylighting and thermal performance analyses. Similarly, Lavin and Fiorito (2017) employed genetic algorithms coupled with daylight and energy simulations to optimize perforation size and distribution for office buildings.

However, empirical studies examining PMV-based thermal comfort conditions in occupied buildings equipped with existing perforated solar screens remain comparatively limited. The unresolved issue addressed in this study is therefore not whether shading devices are generally beneficial, since this has already been widely established in the literature, but how thermal comfort conditions vary across façade o rientations and spatial locations in occupied buildings where perforated solar screens are already installed. This issue is particularly relevant under real operating conditions, where HVAC operation, curtain use, occupancy, and other user-related factors may modify the thermal conditions associated with façade and shading characteristics.

Therefore, there is a need for measurement-based studies that examine thermal comfort conditions associated with existing shading systems in real buildings. Within this context, the present study investigates PMV-based thermal comfort conditions in classrooms and offices located in university buildings oriented along the north–south and east–west axes and equipped with existing perforated solar screens. PMV values obtained from on-site measurements were comparatively analysed at different spatial depths and positions relative to the window, and the results were evaluated in relation to building orientation and façade orientation. By adopting a field-based approach, the study provides a context-specific evaluation that complements the predominantly simulation-based literature on shading performance.

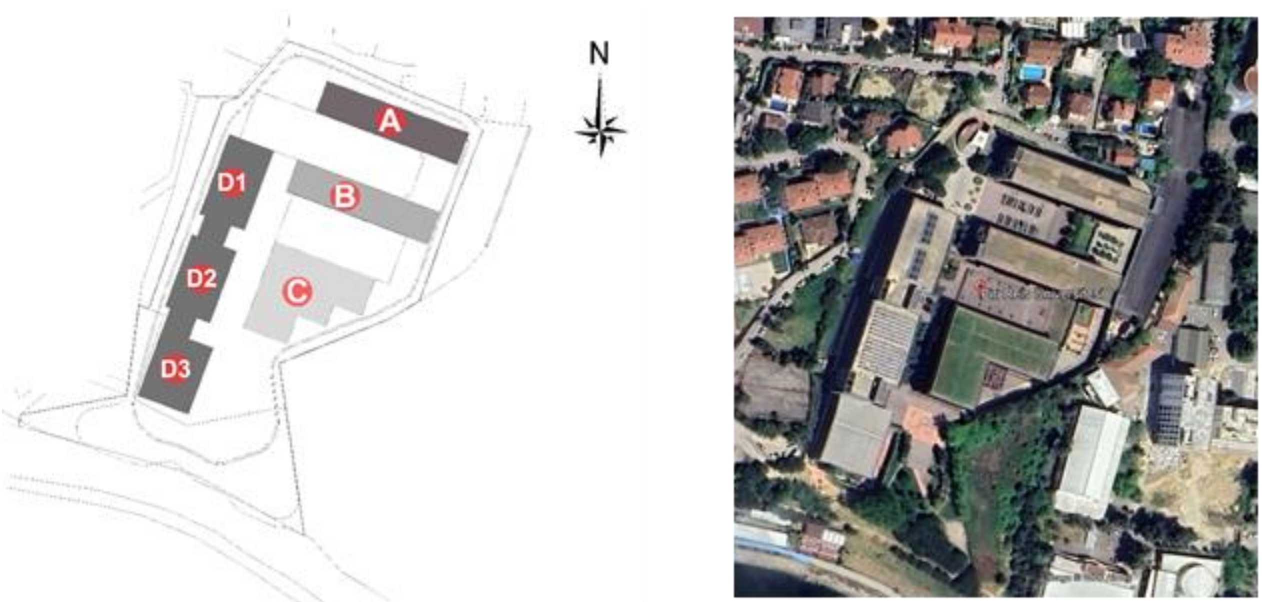
The study specifically examines whether orientation-related variations can be observed in the investigated spaces, how PMV conditions vary with spatial position, particularly between window-adjacent and interior zones, and whether similar perforated solar screen configurations are associated with comparable thermal comfort patterns across different orientations. These aspects provide the analytical framework for the comparative evaluation.

The study does not attempt to isolate the independent causal effect of perforated solar screens under controlled experimental conditions. Rather, it examines thermal comfort patterns observed in occupied spaces and interprets them in relation to façade orientation, existing shading configuration, spatial location, and operational variability. Accordingly, the findings are intended to provide context-specific empirical evidence rather than statistically generalizable conclusions regarding the performance of perforated solar screens.

The contribution of the study lies in complementing the predominantly simulation-based literature with field-based observations obtained from educational and office spaces under actual operating conditions. More specifically, the study provides a spatially differentiated evaluation of PMV conditions by considering façade orientation and distance from the window together. Rather than proposing a new shading geometry or establishing universal orientation-based design principles, the study provides empirical observations that may support the evaluation of existing perforated shading systems and inform further research on orientation-sensitive shading performance.

2. Methodology

This study employed a field-based measurement approach to evaluate the thermal comfort performance of existing perforated shading devices in educational and office buildings. PMV values obtained from on-site measurements were analysed in relation to façade orientation, building orientation, and spatial depth. Within this scope, the field study was conducted in classroom and office spaces located in buildings with different orientations and different shading device types at Piri Reis University Tuzla Campus (Figure 1). In this study, the shading devices were not newly designed or installed; instead, the thermal comfort performance of the existing shading devices used in the buildings was evaluated under real operating conditions.



(a) **(b)**

Figure 1. Site plan and aerial view of Piri Reis University Tuzla Campus: (a) Layout of the blocks where the field study was conducted; (b) Satellite image of the university campus. Sources: (a) Architectural drawings provided by the Technical Department of Piri Reis University; (b) Google Earth, 2026

Piri Reis University Tuzla Campus was selected as the case study area because it contains educational and office buildings with different façade orientations and existing perforated shading systems. The case study buildings were selected purposively to enable a comparative evaluation of thermal comfort performance under similar climatic conditions while representing different building orientations and shading configurations. The selected classrooms and offices represent the most frequently occupied educational and administrative spaces within the campus. All investigated spaces were located within reinforced concrete educational buildings of similar construction period, envelope characteristics, glazing systems, and functional use, thereby reducing variations unrelated to façade orientation and shading performance. The investigated spaces were selected based on comparable functional use, occupancy characteristics, construction systems, glazing properties, and accessibility during the measurement period, while representing different façade orientations and shading configurations. Measurements were performed using the same instruments, identical measurement procedures. All measurements were conducted on the same day to reduce, although not eliminate, variability associated with changing outdoor climatic conditions. The investigated buildings were oriented along the north–south and east–west axes and included different shading device configurations depending on façade orientation. In buildings oriented along the north–south axis, perforated vertical shading devices positioned at an angle to the façade were used, as shown in Figure 2(a). In contrast, in buildings oriented along the east–west axis, perforated shading devices installed parallel to the façade were used, as illustrated in Figure 2(b). These shading devices were part of the existing building façade systems. Table 1 presents the characteristics of the external shading systems used in the investigated buildings. The effects of these shading devices on thermal comfort were evaluated through field measurements conducted under real operating conditions (Figure 3).

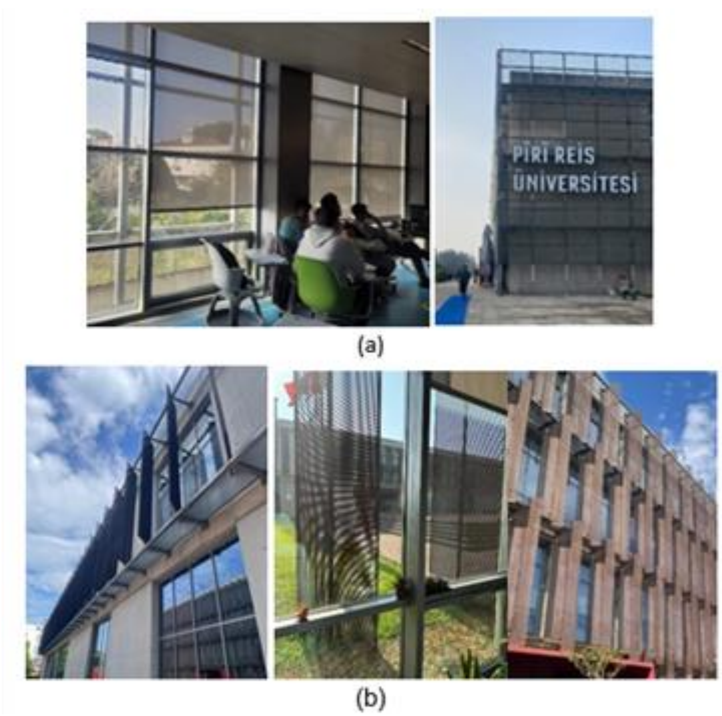


Figure 2. External perforated shading devices used in the buildings: (a) Vertical shading devices oriented towards the North (or North-South axis); (b) Shading devices installed parallel to the South façade (East-West axis.) Source: Prepared by the authors

Table 1. Characteristics of the external shading systems used in the investigated buildings. Source: Prepared by the authors

Building	Façade	Shading type	Panel dimensions	Installation angle	Distance from façade
Block A and B	North/South	Vertical perforated	Approx. 900 × 4660 mm (W × H).	approximately **20°–30°** relative to the façade normal	Approximately **200–300 mm**
Block D	East/West	Parallel perforated	Not available	0 (Parallel to façade)	Approximately **200–300 mm**

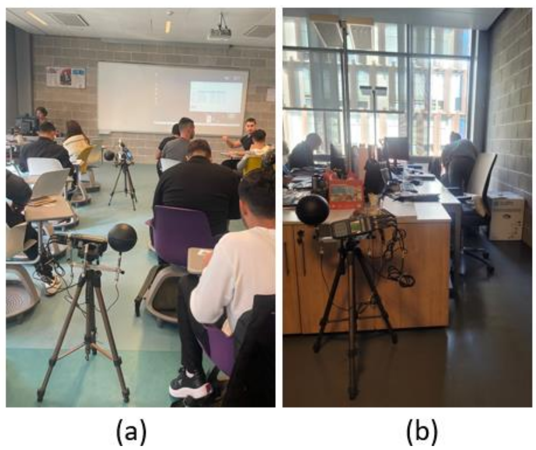


Figure 3. Measurement equipment and sensor layout used during the field study: (a) Measurement points in the classroom; (b) Measurement points in the office space. Source: Prepared by the authors

The measurements were conducted on November 3, 2025, during two measurement periods: late morning (10:00–12:00) and afternoon (13:30–16:00). According to the meteorological records for Istanbul, the daily mean outdoor air temperature on the measurement day was approximately 16 °C, with a daily maximum of approximately 19 °C and a minimum of approximately 13 °C, indicating moderate outdoor thermal conditions during the field measurements.

Thermal comfort evaluation was carried out through in-situ spot measurements. Measurements were conducted at a minimum of two measurement points in each space; in classrooms, the points were determined according to the seating layout, while in offices, measurement points were selected near the window and in the interior zone of the space (Figure 4). This approach allowed the spatial distribution of thermal conditions and the façade effect on different zones within the space to be analysed comparatively.

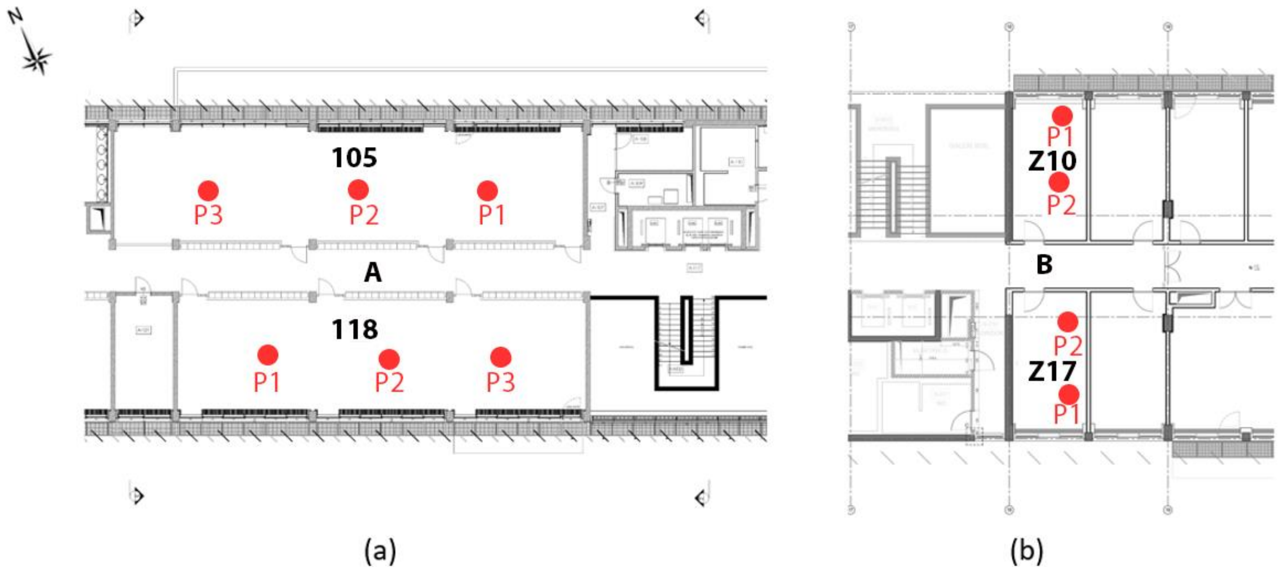


Figure 4. Example floor plans and measurement point locations: (a) Classrooms A105 and A118 in Block A; (b) Office spaces in Block B. Red dots indicate the positioning of sensors at different spatial depths relative to the window. Source: Architectural drawings provided by the Technical Department of Piri Reis University

There was no central building automation system in the investigated spaces, and indoor environmental conditions were controlled through passive strategies (e.g., external shading devices) and manually controlled heating/cooling systems. Since the aim of the study was to evaluate thermal comfort under existing usage conditions, the operation of the heating/cooling systems was left to the users during the measurements. All measurements were conducted under actual operating conditions, and windows remained closed during the measurement periods. Accordingly, HVAC operation and curtain use were intentionally not standardized, as the study sought to capture the influence of shading devices under actual occupancy and operational conditions rather than under controlled laboratory settings. These operational differences were considered part of the real building environment and are discussed as a limitation of the study.

During the field study, the heating/cooling system was active in south-oriented classrooms in the afternoon and in north-oriented classrooms in the morning, and the indoor temperature was set to 16°C by the users in these spaces. In other classrooms and offices, the heating/cooling system was set between 18–22°C or was turned off. In addition, it was observed that curtains were kept closed in some south-oriented classrooms and offices during the measurements.

During the measurement process, air temperature, mean radiant temperature, relative humidity, and air velocity were recorded simultaneously. Measurements were carried out in accordance with the procedures defined in ISO 7730 and ASHRAE 55 standards. All measurements were conducted at a height of 1.10 m from the floor level in accordance with ISO 7726 measurement standards. Thermal comfort evaluation was conducted using the PMV (Predicted Mean Vote) index in accordance with ISO 7730 (2005) and ASHRAE 55 standards. In PMV calculations, the metabolic rate was assumed as 1.2 met, representing sedentary educational and office activities such as reading, writing, and computer-based work. The clothing insulation level was assumed as 0.8 clo, which is considered representative of typical indoor clothing worn during the autumn season. These values were selected in accordance with ISO 7730 recommendations and previous field studies conducted in similar educational environments (Zoroğlu & Zorer Gedik, 2022).

The ideal thermal comfort range was defined as −0.5 < PMV < +0.5, as recommended in ISO 7730 and ASHRAE 55 standards. PMV values obtained from the measurement points were evaluated within this range, and the spatial distribution of thermal comfort within the spaces was analysed.

The measured data were analysed comparatively in relation to façade orientation, building orientation, and spatial depth parameters. In particular, PMV differences between points near the window and interior points were examined to evaluate spatial variations in predicted thermal comfort conditions and the potential for local thermal discomfort.

As this study was designed as a comparative case study rather than a statistically representative survey, the findings should be interpreted within the context of the investigated buildings. Due to the limited sample size, non-parametric statistical methods were adopted. The Mann–Whitney U test was used to compare PMV values between independent groups, including north- and south-oriented classrooms, east- and west-oriented classrooms, and north- and south-oriented office spaces. Differences between window-adjacent (P1) and interior (P2) measurement points in office spaces were evaluated using the Wilcoxon signed-rank test. Statistical significance was assessed at a significance level of $p < 0.05$. The statistical analyses were performed to support the descriptive evaluation of the measured data and to strengthen the interpretation of the observed orientation-related trends within the exploratory scope of the study. In addition, descriptive statistical parameters, including mean values, standard deviations, and minimum–maximum values, were calculated to summarize the variability of the measured PMV values and to support the interpretation of the comparative analyses.

3. Results

3.1. Effect of Façade Orientation on Thermal Comfort

The PMV values obtained from the in-situ measurements revealed orientation- and location-related variations in indoor thermal comfort conditions. In south-oriented office spaces, PMV values measured near the window were generally higher than those measured at interior points and approached or occasionally exceeded the thermal comfort limits. As shown in Figure 5a, higher PMV values were observed particularly at measurement points located close to the window on the south façade. In some measurement points in south-oriented spaces, PMV values reached up to +1.16, indicating warmer predicted thermal conditions at the most exposed measurement location. This trend is further supported by the high radiant-globe temperature values recorded in the same locations (Figure 5b).

In contrast, in north-oriented spaces, PMV values remained within the comfort range of −0.5 to +0.5 at most measurement points, and a more balanced and spatially homogeneous thermal environment was observed compared with the investigated south-oriented offices (Figure 5).

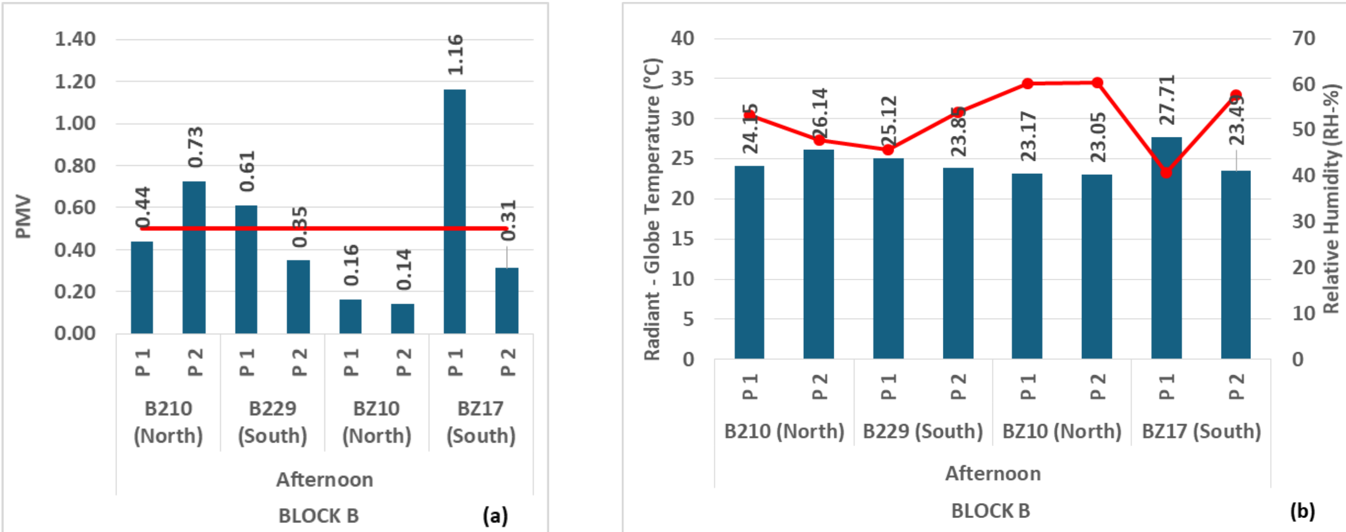


Figure 5. Thermal comfort measurement results for Block B offices in the afternoon: (a) PMV values; (b) Measured Radiant-Globe Temperature and Relative Humidity levels. P1 represents the window-adjacent point and P2 the interior point. Source: Prepared by the authors

PMV measurements conducted in the morning and afternoon in classrooms show that the temporal variation of PMV should be evaluated together with its spatial distribution. In classroom A105, an increasing trend in PMV values was observed at all measurement points in the afternoon, whereas in classroom A118, PMV values generally decreased. In both classrooms, small spatial differences among measurement points were observed during the measurement periods, with ΔPMV values ranging from 0.07 to 0.15 (Figure 6 and Table 2).

The contrasting temporal patterns observed in A105 and A118 should be interpreted in conjunction with differences in façade orientation and HVAC operation, which varied between the investigated classrooms. During the afternoon measurement period, the west-oriented classroom D109 exhibited a higher mean PMV (0.38) than the east-oriented classroom D115 (0.17). Within both classrooms, spatial PMV differences among the measurement points were small (ΔPMV = 0.05 in D109 and 0.08 in D115), indicating relatively limited within-room variation during the measurement period.

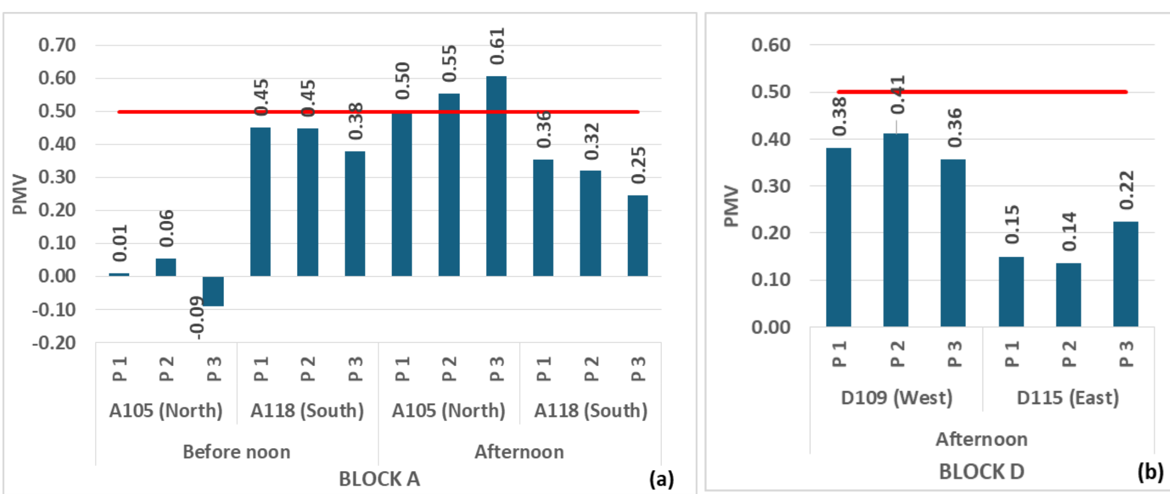


Figure 6. PMV measurement results in classrooms: (a) Block A during morning and afternoon periods; (b) Block D during the afternoon period. Source: Prepared by the authors

To complement the graphical presentation of the measurement results, descriptive statistical indicators (mean, standard deviation, minimum, and maximum PMV values) were calculated for each investigated space. Given the exploratory nature of the study and the limited sample size, the analysis primarily focused on descriptive statistics. Non-parametric statistical tests were additionally performed as a secondary analysis to examine whether the observed PMV differences between façade orientations and measurement locations were statistically significant. Table 2 summarizes the descriptive statistical results obtained for the investigated classrooms and office spaces. Overall, these descriptive statistics are consistent with the orientation-related trends observed in the field measurements. Among the classrooms, the highest mean PMV was recorded in the north-oriented classroom A105 during the afternoon (0.55 ± 0.06), whereas the lowest mean PMV occurred in the east-oriented classroom D115 (0.17 ± 0.04). Among the office groups, south-oriented offices exhibited a higher mean PMV (0.61 ± 0.39) than north-oriented offices (0.37 ± 0.28). In addition, among the individual office spaces, BZ17 exhibited the largest spatial difference between window-adjacent and interior measurement points (ΔPMV = 0.85), indicating greater thermal heterogeneity than the other investigated offices. The larger standard deviation observed in south-oriented offices further indicates greater spatial variability in thermal comfort conditions compared with north-oriented offices.

Table 2. Descriptive statistics of PMV values obtained in the investigated classrooms and office spaces. Source: Prepared by the authors

Space	Orientation	Measurement period	n	Mean PMV	SD	Min	Max	ΔPMV
A105 Classroom	North	Morning	3	-0.01	0.08	-0.09	0.06	0.15
A105 Classroom	North	Afternoon	3	0.55	0.06	0.50	0.61	0.11
A118 Classroom	South	Morning	3	0.43	0.04	0.38	0.45	0.07
A118 Classroom	South	Afternoon	3	0.31	0.06	0.25	0.36	0.11
D109 Classroom	West	Afternoon	3	0.38	0.03	0.36	0.41	0.05
D115 Classroom	East	Afternoon	3	0.17	0.04	0.14	0.22	0.08
North-oriented offices (B210 and BZ10)	North	Afternoon	4	0.37	0.28	0.14	0.73	0.59
South-oriented offices (B229 and BZ17)	South	Afternoon	4	0.61	0.39	0.31	1.16	0.85

Note: ΔPMV = Maximum PMV − Minimum PMV measured within the same classroom. For office groups, ΔPMV is not reported because each orientation group consists of different office spaces. Spatial PMV differences are discussed separately for individual offices

To further examine these descriptive findings, PMV values obtained from north- and south-oriented classrooms (A105 and A118) and east- and west-oriented classrooms (D115 and D109) were compared using the Mann–Whitney U test. The comparisons did not indicate statistically significant differences between the north- and south-oriented classrooms or between the east- and west-oriented classrooms (North–South: p = 0.937; East–West: p = 0.100). The east–west comparison nevertheless showed a descriptive difference during the afternoon measurement period, with higher PMV values in D109 than in D115. Considering the exploratory nature of the case study and the limited sample size, these results should be interpreted as descriptive observation rather than statistically generalizable differences between façade orientations.

3.2. Thermal Comfort Performance of Existing Shading Devices Depending on Façade Orientation

The shading devices examined in this study consist of two different geometric configurations depending on building orientation (Figure 1). In buildings oriented along the north–south axis (Blocks A and B), perforated vertical shading devices positioned at an angle to the façade were used. In the investigated south-oriented offices, higher PMV values were observed near the window, with values approaching or exceeding the upper comfort limit at some measurement points (Figure 5a). Similarly, in west-oriented classroom exhibited higher PMV values than the east-oriented classroom during the afternoon measurement period, even in cases where curtains were closed and the mechanical cooling system was active (Figure 6b).

In buildings oriented along the east–west axis, perforated shading devices installed parallel to the façade were associated with relatively small spatial PMV differences within the investigated east- and west-oriented classrooms. However, since the same shading device geometry was used on both east and west façades and the devices were installed parallel to the façade, the west-oriented classroom exhibited higher PMV values than the east-oriented classroom during the same afternoon measurement period, even in cases where curtains were closed and the mechanical cooling system was active.

The results indicate that the thermal comfort performance of the existing shading devices was not uniform across the investigated façade orientations. While the examined shading devices were present in all investigated spaces, different PMV patterns were observed according to façade orientation and spatial location. However, these patterns should be interpreted together with differences in HVAC operation and curtain use under actual operating conditions.

Similarly, PMV values measured in north-oriented (B210 and BZ10) and south-oriented (B229 and BZ17) office spaces were compared using the Mann–Whitney U test. Although the difference was not statistically significant ($p = 0.486$), descriptive statistics showed higher mean PMV values and greater thermal variability in south-oriented offices. These findings suggest that the most pronounced spatial variation within the investigated office sample occurred in the south-oriented offices, particularly in areas located close to the façade.

3.3. Spatial Distribution of Thermal Comfort Within the Space

The results show that spatial PMV differences were observed among different measurement locations within the investigated spaces. Particularly in south-oriented offices, indoor thermal comfort was not homogeneously distributed, with greater differences observed between window-adjacent and interior measurement points (BZ17 ($\Delta PMV = 0.85$)).

PMV values obtained from three measurement points (P1–P2–P3) in classrooms indicate that the point-based PMV distribution varies depending on the classroom. The maximum difference between P1 and P3 (ΔPMV) ranged between 0.05 and 0.15, and the standard deviation values within classrooms ranged between 0.021 and 0.076. These findings indicate that thermal comfort was more evenly distributed in some classrooms, while spatial variation was more pronounced in others. These observations suggest that measurements at multiple spatial locations may provide additional information on within-room thermal variability compared with a single measurement point.

Measurements conducted in classrooms show that occupants are exposed to different thermal conditions depending on the seating layout. In offices, higher PMV values measured near the window indicate that warmer predicted thermal conditions occurred at some window-adjacent locations. As a result, PMV differences between zones near the window and interior zones were found to reach levels that may affect occupant comfort and work performance. These results show that thermal comfort conditions are not uniformly distributed within the space and are strongly influenced by solar radiation and mean radiant temperature, particularly in perimeter zones close to the façade.

The findings of this study clearly demonstrate the importance of façade orientation-sensitive shading device design. Similarly, Olgyay (1963) emphasizes that solar control strategies in building envelope design should vary depending on façade orientation. These findings indicate that existing shading devices do not provide the same level of thermal comfort performance on all façades, and that indoor thermal comfort, particularly in façades exposed to direct solar radiation, cannot be adequately controlled in terms of spatial distribution. The results suggest that shading device design should be evaluated not only in terms of energy performance but also in terms of achieving a homogeneous distribution of indoor thermal comfort.

Considering the investigated space types separately, different orientation-related patterns were observed. South-oriented offices exhibited the highest individual PMV value and the greatest spatial variability, while north-oriented offices showed comparatively more stable conditions. Among the east- and west-oriented classrooms, the west-oriented classroom exhibited higher PMV values than the east-oriented classroom during the afternoon measurement period. However, the north-oriented classroom A105 also showed relatively high PMV values in the afternoon. Therefore, the findings should not be interpreted as indicating a single performance ranking among façade orientations.

Differences between window-adjacent (P1) and interior (P2) measurement points in office spaces were evaluated using the Wilcoxon signed-rank test. Although the differences were not statistically significant ($p = 0.625$), descriptive analysis indicated considerably larger spatial PMV differences in south-oriented offices than in north-oriented offices. This trend is likely associated with the limited number of paired observations and the exploratory nature of the present case study.

4. Discussion

The present findings address this methodological gap by providing empirical evidence obtained under real operational conditions, allowing the influence of occupant behaviour, HVAC operation, and façade orientation to be evaluated simultaneously. Rather than proposing a new shading geometry, the originality of this study lies in validating the thermal comfort performance of existing perforated solar screens through field measurements and demonstrating orientation-dependent performance differences under actual building operation. Although façade orientation and shading configuration constituted the primary comparative variables in this study, the observed PMV patterns should also be interpreted in conjunction with operational factors such as HVAC settings, curtain use, occupant behaviour, and internal heat gains. Since these variables were intentionally not standardized in order to reflect actual building operation, the measured differences represent the combined influence of façade orientation and operational conditions rather than the isolated effect of the perforated solar screens. While numerous studies have evaluated shading systems through simulation-based approaches, fewer studies have examined the thermal comfort implications of perforated solar screens through field measurements conducted in occupied buildings. Accordingly, this study contributes to the existing literature by providing field-based evidence on the interaction between façade orientation, perforated shading devices, mean radiant temperature, and PMV distribution under actual operating conditions. Unlike simulation-based studies, the present findings demonstrate that orientation-related thermal comfort differences remain observable under real building operation, where occupant behaviour and operational settings introduce additional variability that is difficult to capture through simulation alone.

Olgyay (1963) emphasized that solar control strategies and shading design should be developed according to the sun path and façade orientation. The present findings support this theoretical framework by demonstrating that the thermal performance of perforated solar screens is influenced by orientation-dependent solar exposure under real operating conditions. However, unlike many simulation-based studies, the present research provides field-based evidence obtained under actual operating conditions, where occupant-controlled HVAC operation and shading use also influenced indoor thermal conditions.

These findings suggest that the thermal performance of perforated solar screens should be interpreted as the combined outcome of façade orientation, solar exposure characteristics, and occupant adaptation rather than as the result of shading geometry alone. Variations in PMV are therefore likely to reflect the interaction between solar altitude, exposure duration, operational conditions, and the adaptive actions of occupants.

This interpretation is consistent with Adaptive Comfort Theory, which proposes that occupants continuously modify their behavioural and environmental responses according to changing thermal conditions (de Dear & Brager, 1998; Nicol & Humphreys, 2002). In the present study, occupant-controlled HVAC operation and curtain use represent examples of such adaptive responses. Although occupant behaviour was not quantified through surveys, the observed operational differences indicate that adaptive actions likely contributed to the measured PMV patterns alongside façade orientation and shading configuration.

These findings are consistent with previous studies demonstrating that the thermal comfort performance of shading devices varies according to façade orientation, solar geometry, and climatic conditions (Tzempelikos & Athienitis, 2007; Ochoa & Capeluto, 2008). Tzempelikos and Athienitis (2007) showed that shading devices significantly influence indoor thermal comfort, with their effectiveness varying according to façade orientation and climatic conditions, whereas Ochoa and Capeluto (2008) reported that orientation-specific shading strategies achieve superior thermal and energy performance compared with conventional uniform shading approaches. Consistent with these studies, the present results indicate that orientation-dependent solar exposure remains an important determinant of thermal comfort even under occupied building conditions. Furthermore, because occupant perception surveys were not conducted, the measured spatial PMV differences should be interpreted as differences in predicted thermal comfort conditions rather than direct evidence of occupants' experienced local thermal discomfort.

The comparatively stable thermal conditions observed on north-oriented façades are likely associated with reduced direct solar exposure, which limits the contribution of short-wave solar radiation to mean radiant temperature. Under these conditions, other envelope-related factors such as heat transfer and surface temperatures may become relatively more influential. This finding is consistent with previous studies indicating that north-facing façades receive lower solar gains and therefore provide more stable indoor thermal conditions (Baker & Steemers, 2000). However, heat losses and low surface temperatures should also be considered, particularly during the heating season. ASHRAE (2017) emphasizes the importance of mean radiant temperature in the evaluation of indoor thermal comfort and states that low surface temperatures can significantly affect occupant comfort. This indicates that both solar heat gains and radiant cooling effects should be evaluated together under different seasonal conditions.

Rather than indicating that one façade orientation is inherently associated with poorer thermal comfort, the present findings suggest that thermal performance emerges from the interaction between façade orientation, solar geometry, shading configuration, operational conditions, and occupant adaptation. Consequently, façade orientation should be considered as one component of a broader building-environment system rather than an isolated determinant of indoor thermal comfort.

The orientation-dependent PMV patterns observed in this study can be explained by differences in solar altitude, exposure duration, and radiant heat exchange rather than by façade orientation alone. South-oriented façades are exposed to solar radiation for longer periods throughout the day, resulting in cumulative heat gains and increased surface temperatures. In contrast, east- and west-oriented façades are subjected to lower solar altitude angles during morning and afternoon hours. Under these conditions, solar radiation penetrates deeper into the indoor space and may bypass shading devices that are primarily designed to block high-angle solar exposure.

As a result, façade orientation influences not only the amount of solar radiation received but also the effectiveness of shading devices in controlling solar heat gains. These observations suggest that perforated shading devices installed parallel to the façade may provide less effective solar control during periods of low solar altitude. This situation may lead to spatial variations in radiant and predicted thermal comfort conditions within the space. The relationship between solar altitude angles and mean radiant temperature appears to be particularly important in explaining the observed PMV differences. When low-angle solar radiation enters the space, interior surfaces such as floors, walls, furniture, and glazing can absorb and store solar energy, leading to higher surface temperatures. These warmer surfaces subsequently increase mean radiant temperature, which directly affects occupants' thermal sensation even when air temperature remains relatively stable. Therefore, thermal discomfort near the façade may be more strongly associated with radiant heat exchange than with air temperature alone. Fanger (1970) and ASHRAE 55 state that radiant temperature asymmetry is one of the main environmental factors causing local thermal discomfort in indoor environments. These findings suggest that shading strategies for east and west façades should be evaluated not only in terms of solar radiation control but also by considering changing solar angles and radiation characteristics throughout the day.

Another important finding of the study is that similar shading devices were used on both north- and south-oriented façades in the examined buildings. However, these orientations are exposed to significantly different solar radiation durations and solar altitude angles throughout the year. Therefore, identical shading configurations may not provide the same level of thermal comfort performance on different façade orientations. This finding highlights the importance of climate-responsive, orientation-sensitive, and performance-based façade design approaches, in which shading strategies are adapted to façade-specific solar conditions. Furthermore, the present findings suggest that thermal comfort should be evaluated as a spatially distributed environmental condition rather than solely through room-average indices, particularly in perimeter zones exposed to solar radiationIn this context, the observed spatial variability is likely associated with differences in solar radiation exposure and mean radiant temperature, indicating that shading performance should be assessed not only in terms of reducing air temperature but also in its ability to control radiant heat exchange. Although occupant perception surveys were not conducted, the observed variations in PMV indicate differences in predicted thermal comfort conditions depending on façade orientation and spatial location within the building rather than direct evidence of occupants' experienced local thermal discomfort.

It was also determined that the examined buildings did not have a central building automation system, and that the spaces were mainly operated using passive climate control strategies, while cooling systems were active in south-oriented spaces during the measurement period. Although indoor air temperatures were set to approximately 16°C, PMV values exceeded the comfort range on south façades. These observations suggest that mechanical cooling alone may not always fully compensate for solar heat gains under the investigated operational conditions.

The elevated thermal conditions in perimeter zones further emphasize the dominant role of mean radiant temperature in determining local thermal comfort near glazed façades. Similarly, Tzempelikos et al. (2010) reported that mean radiant temperature increases near glazing façades due to solar radiation and that shading devices can significantly affect thermal comfort in these areas. Their study demonstrated that shading devices can improve indoor thermal comfort by reducing radiant temperature asymmetry. Simulation-based studies in the literature show that climate-responsive shading solutions can improve both energy and thermal comfort performance. Therefore, it is recommended that simulation-based performance analyses and optimization processes should be used together in the design of shading devices.

This study is based on measurements conducted in a limited number of spaces on a specific university campus. Since the measurements were carried out within a specific time period, the results may vary under different seasonal and operational conditions. Nicol and Roaf (2017) emphasized the importance of long-term field data in thermal comfort studies. Therefore, the findings of this study should be considered as context-specific results rather than universally generalizable outcomes, but they can be used as a comparative reference for buildings with similar climatic and architectural conditions.

The study suggests that evaluating the thermal comfort performance of shading devices together with façade orientation, building orientation, and spatial depth may provide a more comprehensive understanding of indoor thermal conditions under real operating environments. The study provides a complementary and context-based contribution to the literature through field-based data collected from university buildings. Unlike many previous simulation-based studies, this study provides field-based evidence on the thermal comfort performance of perforated shading devices under real operating conditions.

The findings of this study are particularly relevant to Mediterranean climatic conditions, which are characterized by high solar radiation levels, prolonged cooling periods, and significant solar exposure throughout much of the year. In Mediterranean regions, shading devices represent a fundamental passive design strategy for controlling solar heat gains, improving indoor thermal comfort, and reducing cooling energy demand. The results may therefore have broader relevance for university campuses and educational buildings in Mediterranean cities, where prolonged solar exposure and seasonal variations in solar altitude can create orientation-dependent thermal conditions. Although the present results are specific to the investigated campus and measurement period, similar challenges may occur in warm and temperate Mediterranean climates, particularly in buildings with highly exposed façades and uniform shading configurations. In this context, the study highlights the potential value of considering façade orientation, solar geometry, and operational conditions together when evaluating existing shading systems and developing climate-responsive design strategies for educational buildings in Mediterranean regions.

4.1. Limitations

Several limitations should be considered when interpreting the findings of this study. The study was conducted on a single university campus. Although the selected buildings provided different façade orientations and shading device configurations, the results may not be directly generalizable to other climatic regions, building types, or institutional settings.

The field measurements were carried out in a limited number of classrooms and office spaces. While the selected spaces were considered representative of the investigated buildings, a larger sample size could provide a more comprehensive understanding of the relationship between façade orientation, shading performance, and thermal comfort. In addition, the study did not include reference spaces without shading devices. Consequently, the findings should be interpreted as comparative observations among existing façade orientations rather than as direct evidence of the isolated effect of shading devices.

The measurements were conducted on a single day during the autumn season. Consequently, the observed thermal comfort conditions represent the climatic characteristics of the measurement period and may differ under summer or winter conditions. In particular, south-, east-, and west-oriented façades are expected to experience greater seasonal variations because solar altitude, solar radiation intensity, and exposure duration change considerably throughout the year. Therefore, long-term measurements covering different seasons would provide a more comprehensive assessment of the annual thermal comfort performance of perforated shading systems and help distinguish orientation-related effects from seasonal climatic variability and improve the generalizability of the findings.

Another limitation is the variation in HVAC operation among the investigated spaces. Since the study aimed to evaluate thermal comfort under actual operating conditions, heating and cooling systems were operated according to user preferences. Consequently, differences in HVAC settings may have influenced the measured thermal comfort conditions. Similarly, curtain usage was not standardized across all spaces. In some south-oriented classrooms and offices, curtains were closed during the measurements, while in others they remained open. This may have affected solar radiation levels and indoor thermal conditions.

Occupant behaviour also represents a limitation of the study. User actions such as operating heating or cooling systems, adjusting curtains, and occupying different locations within the space may have influenced the thermal environment during the measurement periods. In addition, PMV calculations were based on assumed clothing insulation (0.8 clo) and metabolic rate (1.2 met) values derived from ISO 7730 recommendations and previous studies. These assumptions are consistent with ISO 7730 recommendations and are commonly adopted in field studies where individual occupant data cannot be collected. Although these assumptions are widely accepted for educational environments, actual occupant clothing levels and activity patterns may have varied during the measurement period.

Finally, the study focused exclusively on physical measurements and PMV-based thermal comfort assessment. User perception surveys were not conducted. Therefore, the findings reflect predicted thermal comfort conditions rather than occupants' actual thermal sensations, preferences, and satisfaction levels. Future studies integrating both field measurements and occupant surveys could provide a more comprehensive evaluation of thermal comfort performance.

5. Conclusion

This study evaluated the thermal comfort performance of existing shading devices used in educational and office buildings on a university campus through field-based measurements, in relation to façade orientation and building orientation. Field measurements conducted in spaces with different orientations and spatial depths suggest that indoor thermal comfort conditions are influenced by the combined effects of façade orientation, building orientation, and distance from the window under real operating conditions.

The findings suggest that PMV values frequently approached or exceeded the comfort limits in zones close to the window, particularly in south- and west-oriented spaces. In contrast, lower and more stable PMV values were obtained in north-oriented spaces, where indoor thermal conditions were found to be more homogeneous and stable. These findings suggest that existing shading devices may not provide the same thermal comfort performance on different façades and therefore may benefit from evaluation according to façade orientation.

The results show that the impact of shading devices on thermal comfort is not only related to their presence but also to their suitability for façade orientation and solar conditions. In particular, shading devices used on east and west façades may be insufficient to control solar radiation due to low solar altitude angles, which may lead to spatial variations in radiant and predicted thermal comfort conditions. This suggests that, in the investigated buildings, not only the presence of shading devices but also their orientation-sensitive design may play an important role in thermal comfort performance.

Therefore, performance-based shading strategies considering façade orientation, building orientation, and spatial characteristics may provide a more appropriate approach than uniform façade solutions.

This case study contributes to the existing body of knowledge by providing empirical evidence on the relationship between shading devices, façade orientation, and indoor thermal comfort under real operating conditions. While many previous studies have focused primarily on simulation-based assessments, the present study offers field-based measurements that capture actual thermal comfort conditions in occupied university buildings. The study therefore contributes not only by complementing simulation-oriented knowledge through empirical observations, but also by demonstrating that the thermal effectiveness of perforated solar screens varies considerably according to façade orientation under real operational conditions. In this respect, the study adds context-specific data that may support future research on orientation-sensitive shading performance and thermal comfort evaluation. Rather than proposing new shading geometries, the principal contribution of this study lies in providing field-based evidence on the thermal comfort performance of existing perforated solar screens under occupied building conditions, thereby complementing previous simulation-based studies with empirical observations obtained from real building operation.

The findings also have practical implications for architectural design. The results suggest that the application of identical shading solutions on different façades may not always lead to similar thermal comfort outcomes. Therefore, the study provides practical insights that may assist architects and designers in developing more climate-responsive and performance-oriented shading strategies for both new construction and retrofit projects.

Based on the findings of this study, the following recommendations can be made for shading device design:

- Shading devices should not be considered as single-type solutions for all façades; instead, shading strategies should be adapted to façade-specific solar conditions, considering differences in solar altitude, exposure duration, and radiant heat exchange.
- The design of shading devices should be supported by performance data and simulation-based analyses during the early design stage.
- Shading strategies should be evaluated not only in terms of solar radiation control but also in terms of their impact on the spatial distribution of indoor thermal comfort.
- For façades exposed to different solar geometries, shading strategies should be evaluated separately; in particular, low-angle solar exposure on east- and west-oriented façades and prolonged solar exposure on south-oriented façades should be considered in façade-specific design decisions.
- Field measurements should be integrated into the evaluation and improvement processes of shading device design.

In conclusion, the findings of this case study suggest that the thermal comfort performance of shading devices may vary depending on façade orientation, building orientation, and spatial depth. By providing field-based evidence, this case study complements the predominantly simulation-based literature on shading performance. The study offers a measurement-based reference framework for the development of orientation-sensitive shading strategies and may support architectural design and retrofit processes. Furthermore, the findings indicate that the performance of shading devices may benefit from being evaluated not only at the building scale but also at the spatial scale, considering façade orientation and spatial depth. Within the scope of the investigated buildings, the results suggest that shading devices can be considered not only as architectural elements but also as performance-related components that may influence occupant comfort and indoor environmental quality.

Given the exploratory nature of this case study, the limited sample size, and the restricted measurement period, the findings should be interpreted as context-specific rather than statistically generalizable. Nevertheless, the field-based methodology presented in this study may provide a useful framework for future investigations evaluating the thermal comfort performance of shading systems under real operating conditions.

Future research should expand the scope of field-based investigations through long-term monitoring campaigns across different seasons and climatic conditions. Since the present study was based on measurements obtained during a single period, multi-season assessments would provide a more comprehensive understanding of the relationship between façade orientation, shading performance, and thermal comfort. In addition, studies involving a larger number of buildings and different building typologies would improve the generalizability of the findings.

Future studies may also benefit from integrating field measurements with simulation-based analyses to compare predicted thermal comfort performance with conditions measured under actual building operation. Furthermore, the performance of adaptive and dynamic shading systems could be investigated and compared with that of fixed perforated solar screens. Finally, a more holistic assessment could be achieved by integrating thermal comfort evaluation with assessments of daylighting performance, visual comfort, and building energy consumption.

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Conflicts of Interest
The authors report no conflicts of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT Author Statement
All authors contributed equally to the conception, methodology, analysis, writing, and revision of the study. All authors have read and approved the final version of the manuscript.

Contribution to the Field statement
This study contributes to the literature by providing field-based evidence on the thermal comfort performance of existing perforated solar screens in occupied educational and office buildings under actual operating conditions. While previous research has predominantly relied on simulation, this study evaluates PMV based thermal comfort using in-situ measurements across different façade orientations. By examining façade orientation together with building orientation and spatial depth, it demonstrates that identical perforated solar screen configurations may not provide equivalent thermal comfort conditions under real operating conditions. The findings complement existing simulation based research with context specific empirical observations on orientation dependent thermal comfort performance.

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