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Multi-Scalar Thermal Buffering in the Medina of Tunis: Field Measurements and Thermal Perception from Urban Morphology to Courtyard-House Spatial Hierarchies

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This study investigates the role of vernacular spatial configurations in regulating thermal conditions across urban and architectural scales within the Medina of Tunis. Through a multi-scalar framework combining in-situ environmental measurements and thermal perception surveys, the study examines how urban morphology and courtyard-house organization contribute to passive cooling and thermal buffering in a hot Mediterranean climate. Measurements were conducted during summer 2025 across three urban typologies: an open urban node (placette), a narrow urban canyon (alley), and a covered passage (sabbat), as well as within Dar Lasram, a courtyard house. Air temperature, relative humidity, air velocity, globe temperature, and surface temperature were recorded. Spatial differences were more pronounced in globe temperature and radiative heat contribution than in air temperature. The placette reached a globe temperature of 42.60°C, whereas the sabbat recorded 33.45°C, a difference of 9.15°C in late morning. Dar Lasram exhibited lower and progressively delayed temperature peaks from the Principal Patio toward transitional and enclosed spaces. Thermal perception similarly varied across the spatial hierarchy, with warmer sensations in more exposed spaces and moderated sensations in protected environments. These findings highlight the Medina's multi-scalar thermal buffering capacity through the sequential organization of spaces with contrasting degrees of exposure, shading, and enclosure.

Introduction

Climate change and rapid urbanization are intensifying urban thermal stress, particularly in Mediterranean and hot-arid regions, where rising temperatures, frequent heatwaves, and urban heat island effects increase pressure on built environments to provide thermal comfort while minimizing building energy demand.[1] In this context, the increasing reliance on mechanical cooling is environmentally and economically unsustainable, prompting renewed interest in passive, climate-responsive and low-energy architectural strategies.

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1. UN-Habitat, *World Cities Report 2024: Cities and Climate Action* (UN-Habitat, 2024); UNESCO, *Climate change in Mediterranean World Heritage cities* (UNESCO, 2025).

Vernacular architecture, developed through long-term adaptation to local climatic conditions, offers valuable insights into climate-responsive design.[2] Among these, the historic fabric of the Medina of Tunis represents a relevant example of an urban system shaped by environmental constraints and socio-cultural practices. Characterized by compact morphology, narrow shaded alleys, introverted courtyard houses, and complex spatial sequences, the Medina demonstrates an embedded capacity for passive thermal regulation.[3] These interconnected spatial configurations create successive degrees of exposure and enclosure, allowing thermal conditions to be moderated across multiple spatial scales through shading, thermal mass, and controlled exposure.

While the climatic responsiveness of traditional urban fabrics has been widely acknowledged, quantitative field-based evaluations integrating urban and architectural scales with human thermal perception remain limited.[4]

Existing research on thermal environments in traditional settlements often focuses either on urban-scale microclimate dynamics or on building-scale indoor performance, with limited integration between these scales.[5] Furthermore, many studies rely primarily on physical environmental indicators, overlooking the role of thermal perception, adaptive behavior, and spatial use patterns in shaping comfort. As a result, the thermal relationships between exposed urban spaces, shaded passages, courtyard spaces, transitional zones, and enclosed interiors remain insufficiently understood within a single multi-scalar framework integrating environmental measurements and human thermal perception.[6]

To address this gap, this study investigates the Medina of Tunis as an integrated climate-responsive system. The research aims to evaluate how spatial configuration influences microclimatic conditions and thermal perception across urban and architectural scales, and how these spatial scales contribute to multi-scalar thermal buffering within the Medina. Accordingly, the study is guided by the following research questions:

1. How do spatial typologies at the urban scale (open nodes, narrow canyons, and covered passages) and architectural scale (courtyards, transitional spaces, and interior spaces) influence microclimatic conditions?
2. What passive cooling mechanisms are associated with the observed thermal variations across these spatial configurations?
3. How do occupants perceive and adapt to these microclimatic differences?

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2. L. E. D'amato, and S. Kapoor, "Climate Responsive Strategies in Vernacular Architecture: A Comparative Analysis at Various Latitude," *International Research Journal of Multidisciplinary Scope* 5, no. 4 (2024): 1047-1068.

3. R. Benbrahim, and L. Sriti, "Cultural and Bioclimatic Insights from the Vernacular Architecture of the Casbah of Algiers: A Model for Sustainable Future," *International Journal of Innovative Technologies in Social Science* 1, no. 45 (2025).

4. J. M. F. Pardo, "Challenges and Current Research Trends for Vernacular Architecture in a Global World: A Literature Review," *Buildings* 13, no. 1 (2023): 162.

5. G. Cherchi, A. Santus, D. R. Fiorino, and S. Ferrari, "Microclimate Assessment and Outdoor Human Comfort Enhancement of a Historic Village in Sardinia, Italy," *Urban Planning* 10 (2025): 10708.

6. T. Liu, Y. Wang, L. Zhang, N. Xu, and F. Tang, "Outdoor Thermal Comfort Research and Its Implications for Landscape Architecture: A Systematic Review," *Sustainability* 17, no. 5 (2025): 2330.

To answer these questions, a multi-method approach is adopted, combining in-situ environmental measurements and occupant-based thermal perception surveys. Field measurements conducted during the summer of 2025 recorded air temperature, relative humidity, globe temperature, air velocity, and surface temperature across representative urban and architectural spatial typologies. These data are complemented by survey data capturing subjective comfort and adaptive practices.

Unlike studies that examine urban microclimate or building performance independently, the research explores how thermal conditions are progressively moderated across interconnected urban and architectural spatial sequences, from exposed public spaces to buffered interior environments.

This paper first reviews relevant literature on vernacular passive cooling, urban microclimate, and thermal perception in Mediterranean environments. It then presents the research methodology, including field measurements and thermal perception surveys. The subsequent sections discuss the environmental results and their implications for climate-responsive urban design before concluding with the main findings and research contributions.

Literature Review

Vernacular Urban Morphology and Passive Cooling

Historic medinas represent climate-responsive urban systems in which spatial configuration, architectural morphology, and environmental adaptation are closely interconnected. The Medina of Tunis reflects centuries of passive environmental adaptation to hot Mediterranean climatic conditions through its compact urban form, shaded circulation networks, courtyard-based architecture, and transitional spatial sequences.[7] Traditional Islamic and North African architecture employs multiple passive cooling strategies through the deliberate manipulation of light, shadow, airflow, and enclosure.[8] Courtyards, arcades, and covered passages reduce radiative heat gain while stabilizing microclimatic conditions and improving natural ventilation,[9] and field investigations in comparable medinas such as the Algiers Casbah have confirmed measurable thermal comfort differences between enclosed and exposed environments.[10]

At the urban scale, geometric parameters such as aspect ratio (H/W), sky view factor (SVF), and street orientation strongly govern solar exposure, airflow, and radiative heat exchange,[11] with compact configurations and reduced SVF consistently

7. X. Du, "Passive cooling techniques," *A+BE | Architecture and the Built Environment* 10 (2019): 60-100.

8. C. Abdalla, and A. Yousif, "Functional Performance of Light and Shadow in Islamic Architecture," *Architecture Image Studies* 6, no. 4 (2025): 1210-1220.

9. X. Zhou, E. Antonini, and J. Gaspari, "Impact of Courtyard Microclimate on Building Thermal Performance Under Hot Weather Conditions: A Review," *Energies* 18, no. 20 (2025): 5433.

10. F. H. Arrar, D. Kaoula, M. E. Matallah, A. Abdessemed-Foufa, M. Taleghani, and S. Attia, "Quantification of Outdoor Thermal Comfort Levels under Sea Breeze in the Historical City Fabric: The Case of Algiers Casbah," *Atmosphere* 13, no. 4 (2022): 575.

11. G. Mihalakakou, J. A. Paravantis, P. Nikolaou, S. Malefaki, A. Romeos, A. Fotiadi, et al.,

linked to improved thermal comfort in historic urban fabrics.[12] Previous studies further indicate that higher H/W ratios can enhance street shading by reducing direct solar exposure, while lower SVF limits sky exposure and associated radiative gains at pedestrian level. Street orientation also influences the timing and duration of solar access within urban canyons, thereby affecting the temporal distribution of radiative exposure.[13] Beyond urban form, heavy masonry walls and semi-enclosed configurations further contribute to delayed heat transfer and temporal thermal buffering through thermal mass and progressive spatial attenuation.[14]

These mechanisms are directly relevant to the Medina of Tunis, where compact morphology, shaded alleys, and covered passages such as the sabbat represent spatial configurations identified in the literature as effective for passive thermal regulation.

Outdoor Thermal Stress and Radiative Exposure

Outdoor thermal comfort is governed not only by air temperature but also by radiative heat exchange, solar exposure, humidity, and airflow.[15] In hot Mediterranean climates, radiative heat gain is often the dominant contributor to thermal stress, making globe temperature and mean radiant temperature more reliable indicators of pedestrian discomfort than air temperature alone.[16] Studies confirm that enclosed and shaded urban typologies exhibit substantially lower mean radiant temperatures than exposed open spaces, and that air temperature alone may mask these critical differences.[17] While integrated indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) capture these combined effects,[18] their predictive reliability is limited in naturally ventilated historic

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"Urban Canyon Geometry and Green Infrastructure: A Review of Strategies for Enhancing Thermal Comfort and Microclimate," *Sustainability* 18, no. 9 (2026): 4335.

12. B. Lai, J.-M. Fu, C.-K. Guo, D.-Y. Zhang, and Z.-G. Wu, "Street Geometry Factors Influencing Outdoor Pedestrian Thermal Comfort in a Historic District," *Buildings* 15, no. 4 (2025): 613.

13. Ibid; Mihalakakou, Paravantis, Nikolaou, Malefaki, Romeos, Fotiadi, et al., "Urban Canyon Geometry and Green Infrastructure: A Review of Strategies for Enhancing Thermal Comfort and Microclimate," 2026: 4335.

14. A. Racha, and S. Kacher, "Towards a Better Knowledge of Traditional Environmental Devices: Comparison Between Two Traditional Algerian Houses," in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIV-M-1–2020*, 1065-1072. HERITAGE2020 (3DPast | RISK-Terra) International Conference on Vernacular Architecture in World Heritage Sites. Risks and New Technologies, 12 September 2020, Valencia, Spain.

15. T. Liu, Y. Wang, L. Zhang, N. Xu, and F. Tang, "Outdoor Thermal Comfort Research and Its Implications for Landscape Architecture: A Systematic Review," *Sustainability* 17, no. 5 (2025): 2330.

16. Ibid; M. W. Yahia, E. Johansson, S. Thorsson, F. Lindberg, and M. I. Rasmussen, "Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania," *International Journal of Biometeorology* 62, no. 3 (2018): 373-385.

17. Arrar, Kaoula, Matallah, Abdessemed-Foufa, Taleghani, and Attia, "Quantification of Outdoor Thermal Comfort Levels under Sea Breeze in the Historical City Fabric: The Case of Algiers Casbah," 2022, 575; Z. Yao, P. Wang, Y. Tian, Y. Zhang, Q. Zhang, X. Wang, et al., "Impact of Sky View Factor on Seasonal Microclimate and Thermal Comfort Variability Across Urban Campus Streets and Buildings," *Buildings* 15, no. 22 (2025): 4121.

18. Liu, Wang, Zhang, Xu, and Tang, "Outdoor Thermal Comfort Research and Its Implications for Landscape Architecture: A Systematic Review," 2025, 2330.

environments where occupants exhibit strong adaptive behavior and tolerance.[19] The literature therefore emphasizes the importance of considering radiative exposure alongside subjective thermal perception when assessing outdoor thermal conditions in naturally ventilated historic environments.

Courtyard Houses and Architectural Thermal Buffering

Courtyard houses constitute one of the most characteristic architectural typologies of the Medina of Tunis and play a central role in passive environmental regulation.[20] Through enclosure, shading, thermal mass, and spatial sequencing, courtyard-centered houses create buffered indoor environments capable of moderating short-term climatic fluctuations.[21] Enclosed and transitional spaces, courtyards, entrance sequences, semi-open galleries, and intermediary zones function as environmental filters that progressively reduce radiative heat transfer before it reaches deeper interior rooms, while thermal inertia from heavy masonry construction further contributes to delayed and stabilized thermal response.[22] These mechanisms are particularly significant in hot Mediterranean climates where reducing daytime radiative heat gain is essential for natural ventilation comfort,[23] and the performance of courtyard houses reflects the integrated relationship between geometry, materiality, enclosure, and spatial hierarchy rather than any single element.

Research Gap and Multi-Scalar Thermal Regulation

The three bodies of literature reviewed above converge on a shared insight: passive thermal regulation in historic medinas is not produced by isolated elements but by the combined and sequential operation of urban morphology, radiative shielding, and architectural spatial hierarchy. Vernacular urban form controls exposure through compact geometry and reduced sky view; differences in radiative exposure may be more clearly reflected by globe temperature than by air temperature alone; and courtyard houses attenuate heat progressively through transitional spatial sequences and thermal inertia. Yet despite this convergence, most existing research examines these mechanisms in isolation, focusing either on urban-scale outdoor microclimate or on building-scale indoor performance, and rarely integrates physical environmental data with occupant thermal perception across both scales simultaneously.[24]

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19. F. R. Akbar Rahman, "Diurnal Thermal Comfort Variations and Model-User Perception Gaps in a Tropical Peatland Campus," *Journal of Hunan University Natural Sciences* 52, no. 6 (2025).

20. Abdalla, and Yousif, "Functional Performance of Light and Shadow in Islamic Architecture," 2025, 1210-1220.

21. Racha, and Kacher, "Towards a Better Knowledge of Traditional Environmental Devices: Comparison Between Two Traditional Algerian Houses," in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIV-M-1–2020*, 1065-1072. HERITAGE2020 (3DPast | RISK-Terra) International Conference on Vernacular Architecture in World Heritage Sites. Risks and New Technologies, 12 September 2020, Valencia, Spain.

22. Ibid.

23. Yahia, Johansson, Thorsson, Lindberg, and Rasmussen, "Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania," 2018, 373-385.

24. Y. Toparlar, B. Blocken, B. Maiheu, and G. J. F. Van Heijst, "A review on the CFD analysis

The relationships between exposed urban nodes, shaded alleys, courtyard spaces, and enclosed interior rooms therefore remain insufficiently documented through integrated field-based approaches. This study addresses that gap by treating the Medina of Tunis as a multi-scalar climate-responsive system and combining environmental measurements, architectural-scale thermal analysis, and a thermal perception survey to evaluate how vernacular spatial configurations regulate thermal stress continuously from the urban fabric to the interior room.

Methodology

Research Framework

This study adopts a multi-scalar approach to investigate the passive cooling performance of the Medina of Tunis. The research framework integrates quantitative environmental measurements with qualitative human-centred thermal perception assessment to examine the relationships between urban morphology, microclimate, and spatial experience. The methodology is structured around two complementary components:

- Field measurements across representative urban and architectural spatial typologies.
- Thermal perception surveys assessing subjective comfort.

This integrative approach enables comparison between measured thermal conditions and subjective thermal perception, linking physical environmental variations with human responses across the investigated spatial typologies.

Case Study Context

The study is situated in the historic Medina of Tunis, located at the core of Tunis, the capital of Tunisia (Figure 1). Situated within the Mediterranean basin at the northern edge of Africa, the Medina stands as one of the region's most significant examples of vernacular heritage. The Medina is characterized by a dense and compact urban fabric in which narrow and winding streets, cul-de-sacs, small open spaces, and locally covered passages are closely interwoven with an inward-oriented architecture organized predominantly around courtyards. The continuity of the built frontage, variations in street width, and intermittent openings and overhead enclosures create varying degrees of openness and enclosure, establishing a spatial transition from confined public circulation routes to transitional and enclosed architectural spaces. These characteristics define the distinctive spatial complexity of the Medina across urban and architectural scales.

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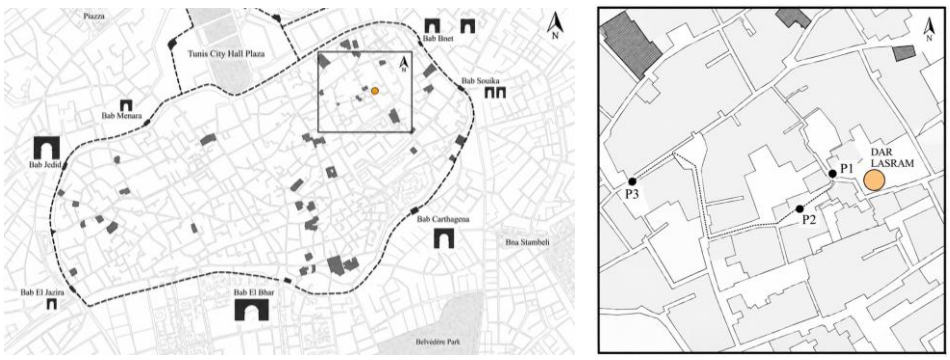
of urban microclimate," *Renewable and Sustainable Energy Reviews* 80 (2017): 1613-1640; Q. Yu, G. Ketzler, G. Mills, and M. Leuchner, "Exploring the integration of urban climate models and urban building energy models through shared databases: A review," *Theoretical and Applied Climatology* 156, no. 5 (2025): 266.

(a) (b) (c)

Figure 1. *Study Area Location Showing (a) Tunisia and the Location of Tunis, (b) Tunis and the Location of the Medina, and (c) the Medina of Tunis*
Source: Authors' illustration.

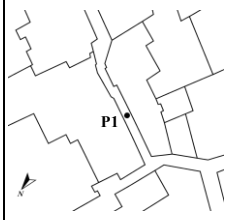
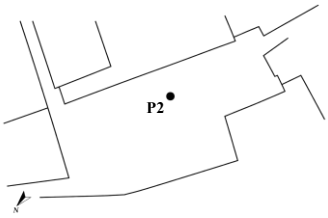
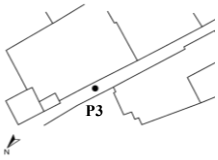
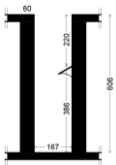
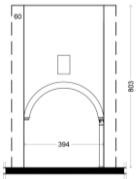
At the urban scale, three spatial configurations were selected within the study area shown in Figure 2 to capture contrasting morphological conditions within this heterogeneous fabric: P1, a narrow urban canyon (alley); P2, an open urban node (placette); and P3, a covered passage (sabbat). Their selection reflects progressive differences in openness, overhead enclosure, sky exposure, and direct solar access, allowing microclimatic conditions to be compared across distinct but spatially related urban configurations. The placette represents the most open condition, characterized by greater sky exposure and direct solar access; the alley represents an intermediate condition, where the narrow street geometry restricts sky exposure and solar penetration; and the sabbat represents the most enclosed condition, where overhead coverage substantially limits both sky exposure and direct solar access. These typologies therefore encompass contrasting degrees of enclosure and exposure within the Medina, ranging from the relatively exposed placette to the highly enclosed sabbat (Table 1).



(a) (b)

Figure 2. *Study Locations within the Medina of Tunis: (a) Medina of Tunis and (b) Urban Measurement Points (P1 Alley, P2 Placette, and P3 Sabbat) and Dar Lasram*
Source: Authors' illustration.

Table 1. *Typomorphological Characteristics of the Investigated Urban Typologies, Including Measurement Locations, Representative Sections, and Site Photographs of the Alley (P1), Placette (P2), and Sabbat (P3) within the Medina of Tunis*

Urban Typology	**P1 Alley** Alley "Rue La Noria"	**P2 Placette** Placette "Palais Kheireddine"	**P3 Sabbat** Sabbat "Rue du Pasha"
Location map			
Representative Section			
Site Photo			

Source: Author's illustration. Photographs: P1 and P3, courtesy of Khouloud Hamrouni; P2, Wikimedia Commons (2010), public domain.

At the architectural scale, the investigation focused on Dar Lasram, a traditional courtyard house whose spatial organization provides a sequence of courtyards, transitional, and enclosed spaces. Originally constructed as a large palatial residence, Dar Lasram represents the spatial organization of an affluent traditional Tunisian dwelling, with residential, service, reception, and guest functions distributed through a hierarchical arrangement of spaces.[25] Dar Lasram was selected for its well-preserved architectural configuration, accessibility for field investigation, and spatial organization, which incorporates two courtyards with contrasting degrees of exposure, namely the partially covered Principal Patio and the uncovered Service Patio, as well as two distinct transitional spaces, the Skifa and Driba, leading toward enclosed interior spaces (Figure 3). This configuration enables thermal conditions to be examined across levels of exposure and enclosure within the courtyard-house spatial hierarchy.

25. J. Revault, *Palais et demeures de Tunis: (XVIIIe et XIXe siècles)* (Editions du Centre national de la recherche scientifique, 1983).

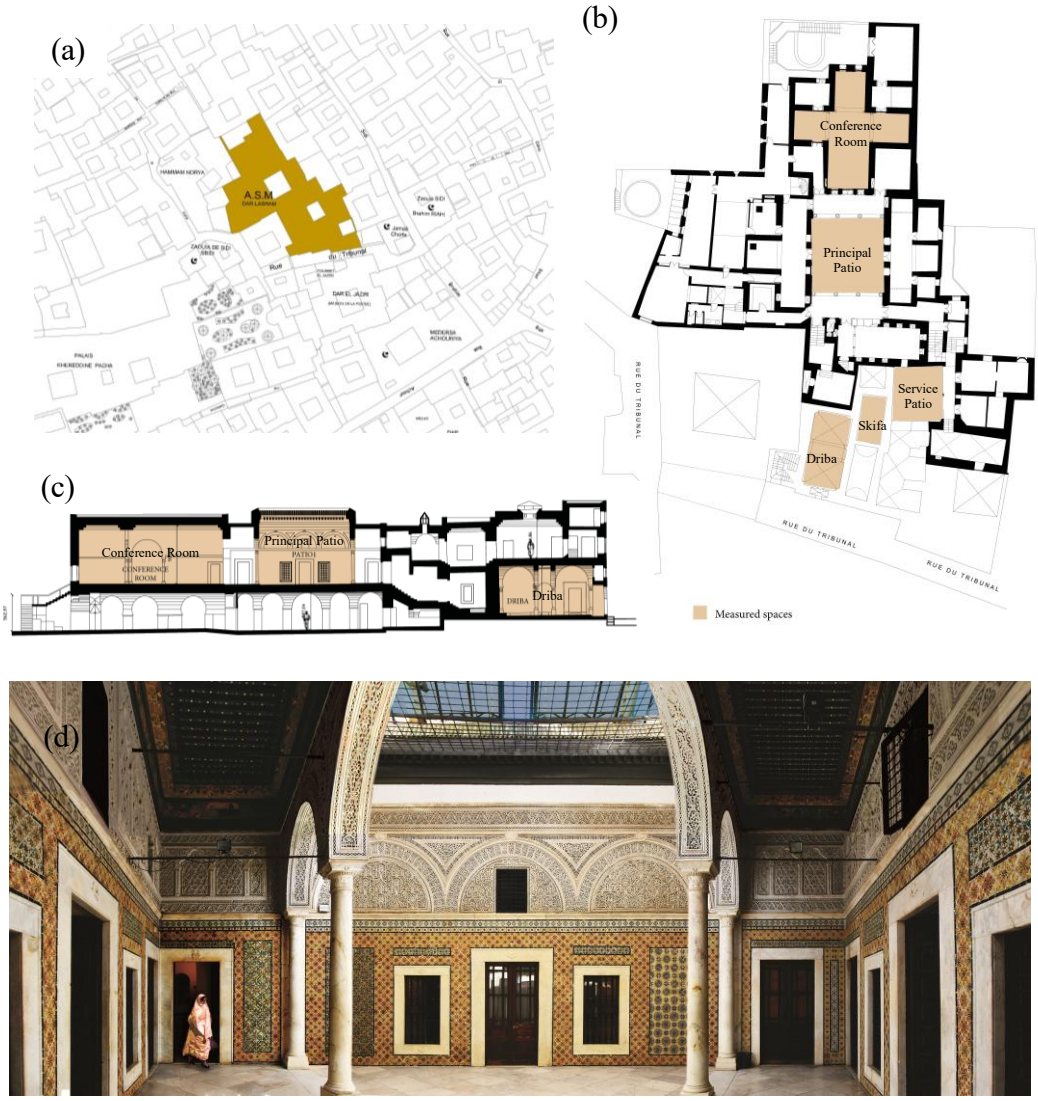


Figure 3. *Dar Lasram: (a) Site Plan, (b) Plan, (c) Section, and (d) Principal Patio*
Source: Authors, adapted from the Association de Sauvegarde de la Médina de Tunis (ASM). Photograph: (d), courtesy of Hamadi Rgayeg.

Field Measurements

In-situ environmental measurements were conducted during August 2025 to characterize thermal conditions under naturally ventilated conditions during the peak summer period. The recorded parameters included air temperature (Ta, °C), relative humidity (RH, %), air velocity (Va, m/s), globe temperature (Tg, °C), and surface temperature (Ts, °C). Additional outdoor measurements of air temperature, relative humidity, air velocity, and solar radiation (W/m²) were conducted on the rooftop of a nearby building. Among these parameters, the comparative analysis presented in this study focuses on temperature-related indicators (Ta, Tg, and Ts) to characterize spatial variations in thermal conditions and radiative exposure across the investigated typologies. Infrared thermography was employed as a complementary diagnostic tool to assess surface temperature distributions across the selected urban

typologies. Thermal images were captured at two-hour intervals during six measurement rounds between 08:00 and 18:00 at the three representative sites: "Rue La Noria" (alley), "Palais Kheireddine" (placette), and "Rue du Pasha" (sabbat). Representative surface temperatures (Ts) of ground surfaces, walls, doors, and shading elements were measured using an infrared thermometer and documented through thermal imagery to identify surface-temperature patterns associated with differences in solar exposure and shading.

Urban environmental measurements were conducted at three representative urban spatial typologies within the Medina of Tunis: an exposed placette (P2), a narrow alley (P1), and a covered passage or sabbat (P3). These locations were selected to represent different levels of enclosure, solar exposure, and sky view factor within the urban fabric. Air temperature (Ta, °C), relative humidity (RH, %), air velocity (Va, m/s), and globe temperature (Tg, °C) were measured at a height of approximately 1.2 m above ground level, corresponding to pedestrian thermal exposure. Measurements were performed using a rotational transect approach at two-hour intervals between 08:00 and 18:00, comprising six measurement rounds, to capture diurnal variations in microclimatic conditions across the urban spatial hierarchy. Measurements were conducted sequentially across the selected urban typologies. As observations were not recorded simultaneously, the connecting lines used in the graphical representations are intended solely to facilitate visualization of temporal patterns and do not represent continuous monitoring or interpolated values between measurement intervals.

Field measurements were conducted in Dar Lasram during August 2025 to characterize indoor thermal behavior under naturally ventilated operating conditions within the historic courtyard house. Continuous on-site monitoring was performed to characterize thermal and hygrothermal conditions within the investigated spaces. Indoor environmental parameters included air temperature (°C), relative humidity (%), air velocity (m/s), surface temperature (°C), and globe temperature (°C). Air temperature and relative humidity were measured using ESPEC RS-13 and RS-14 data loggers, providing an accuracy of approximately ±0.5°C for temperature and ±5% RH for humidity. Air velocity measurements were conducted using a Testo 440 multifunction anemometer equipped with a hot ball probe (Ø 3 mm), suitable for detecting low indoor air speeds typical of naturally ventilated environments. Surface temperatures were measured using thermocouples connected to a MIDI temperature data logger. Globe temperature was recorded using a 150-mm-diameter black globe thermometer. All indoor sensors were positioned at a height of 1.2 m above floor level, corresponding to the occupied zone for standing and mixed-use activities, and placed away from direct solar radiation and localized heat sources. Measurements were recorded at 10-minute intervals continuously throughout the monitoring period. Monitoring locations were selected to represent different spatial conditions and courtyard relationships within the building, including the Principal Patio (partially covered), Skifa, Driba, Conference Room, and Service Patio (uncovered). The Principal Patio, Skifa, Driba, and Conference Room were monitored during the main campaign from 9 to 15 August 2025, while the Service Patio was monitored during a subsequent measurement period from 17 to 21 August 2025,

due to the limited number of monitoring instruments available for simultaneous deployment.

For graphical presentation and comparative analysis, 11 August 2025 was selected as the representative day for the urban measurements and the main Dar Lasram spatial sequence. As the Service Patio was monitored during the subsequent measurement period, its profile from 18 August 2025 was selected for comparative visualization and superposed with the 11 August profiles of the Principal Patio, Skifa, Driba, and Conference Room. This comparison is intended to illustrate relative diurnal thermal behavior rather than simultaneous spatial temperature differences.

Thermal Perception Survey

To incorporate the human dimension of thermal comfort, a thermal perception survey was conducted within the study area to investigate subjective thermal sensation, spatial usage patterns, and adaptive behaviors across different urban and architectural spatial typologies. The survey was administered during morning, midday, and evening periods corresponding to the environmental measurement sessions. Participants evaluated their thermal sensation using the ASHRAE seven-point Thermal Sensation Vote (TSV) scale ranging from cold (-3) to hot (+3) (Table 2).[26] Mean TSV values and the observed minimum–maximum range were calculated for each spatial typology and time period to characterize both the central tendency and variability of thermal perception responses.

A total of 30 participants took part in the thermal perception survey, comprising 16 males (53.3%) and 14 females (46.7%). Participants represented three age groups: 20–29 years (63.3%), 30–39 years (23.3%), and 40–49 years (13.3%). The sample included equal numbers of residents and visitors (n = 15 each), providing a balanced representation of participants with different levels of familiarity with the Medina environment. Participants were surveyed across different urban and architectural spatial typologies, enabling the assessment of thermal perception under varying environmental conditions. Within Dar Lasram, thermal perception was evaluated across the Principal Patio (partially covered), Service Patio (uncovered), Skifa, Driba, and Conference Room to examine the relationship between measured environmental conditions and occupant perception within the courtyard-house spatial hierarchy. The survey periods were aligned with the environmental measurement sessions to support comparison between measured thermal conditions and subjective thermal perception.

Table 2. *Thermal Sensation Scale Used in the Thermal Perception Survey (Adapted from ASHRAE 55)*

Thermal Sensation Vote (TSV)	**-3**	**-2**	**-1**	**0**	**+1**	**+2**	**+3**
Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Source: Authors.

26. ASHRAE. *ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023).

Data Integration and Analysis

The datasets obtained from field measurements and thermal perception surveys were analyzed in an integrated framework to identify relationships between spatial configuration, measured thermal conditions, and thermal perception. Comparative analyses across spatial typologies were conducted to assess:

- Thermal differences between exposed and sheltered spatial configurations.
- Thermal variation across the courtyard-house spatial sequence.
- The relationship between measured environmental conditions and subjective thermal perception.

This integrated analysis provides a basis for identifying how thermal conditions and perceived thermal responses vary with spatial configuration. Figure 4 presents the methodological framework of the study, integrating environmental measurements and thermal perception surveys within a multi-scalar thermal buffering assessment.

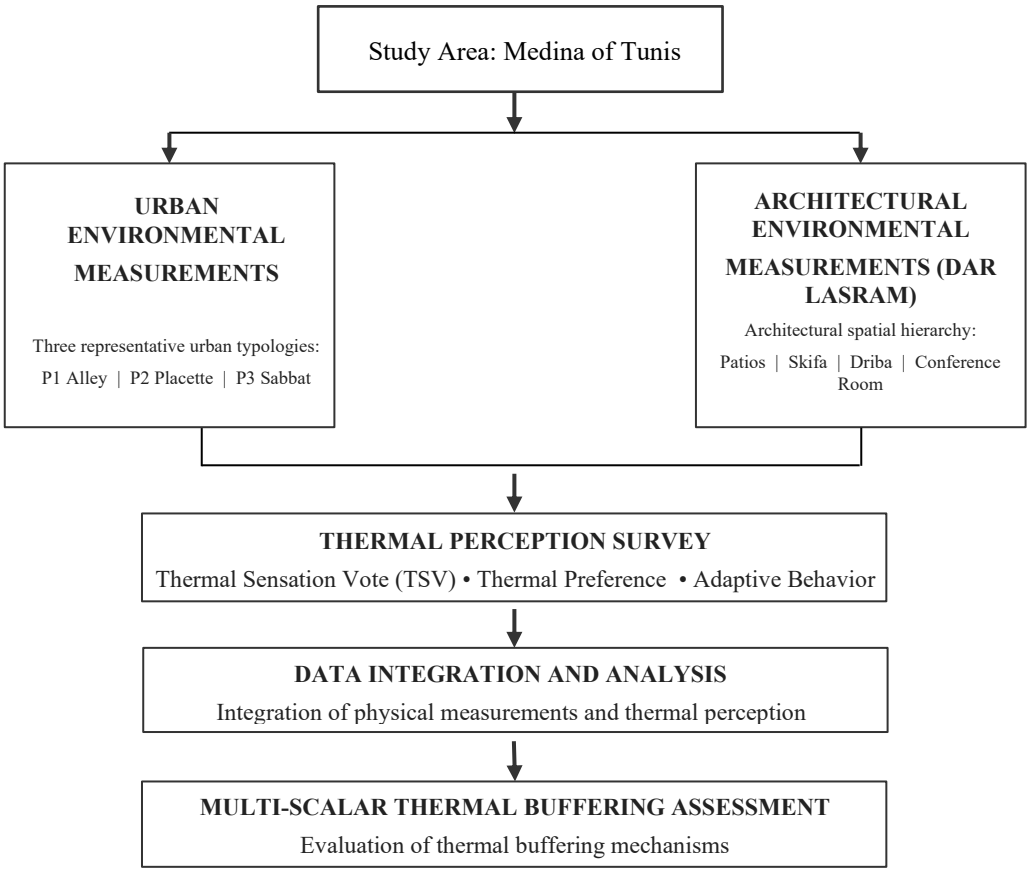


Figure 4. *Methodological Framework of the Study*
Source: Authors.

Results

Air Temperature Variation across Spatial Typologies

Diurnal air-temperature differences across the investigated spatial typologies varied throughout the day, with the largest difference of 5.86°C observed between the exposed placette (P2) and the sabbat (P3) during the 10:00–11:00 period (Figure 5). The placette exhibited the highest air temperature during this period (38.47°C), compared with 32.61°C in the sabbat. From midday onward, the pattern shifted, with the alley becoming warmer than the placette and reaching its largest difference at 14:00–15:00. The sabbat generally maintained lower air temperatures than the other typologies, particularly during the late morning, while differences between the three spaces narrowed toward the evening.

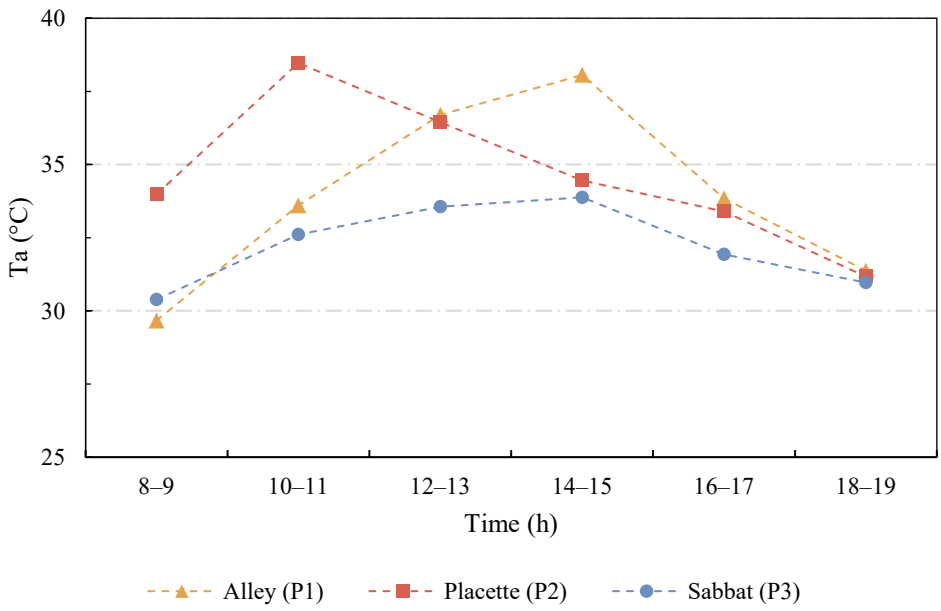


Figure 5. *Diurnal Variation of Ta (°C) across Spatial Typologies in the Medina of Tunis*
Source: Authors.

Radiative Thermal Stress (Globe Temperature)

Figure 6 illustrates the diurnal variation in globe temperature (Tg) across the three urban typologies. Compared with air temperature, Tg exhibited more pronounced differences between spatial configurations. The exposed placette (P2) reached a maximum Tg of 42.60°C during the 10:00–11:00 period, while the sabbat (P3) recorded 33.45°C during the same period, corresponding to a difference of 9.15°C. The alley (P1) exhibited an intermediate but more variable pattern, with Tg exceeding that of the placette (P2) during several later measurement periods.

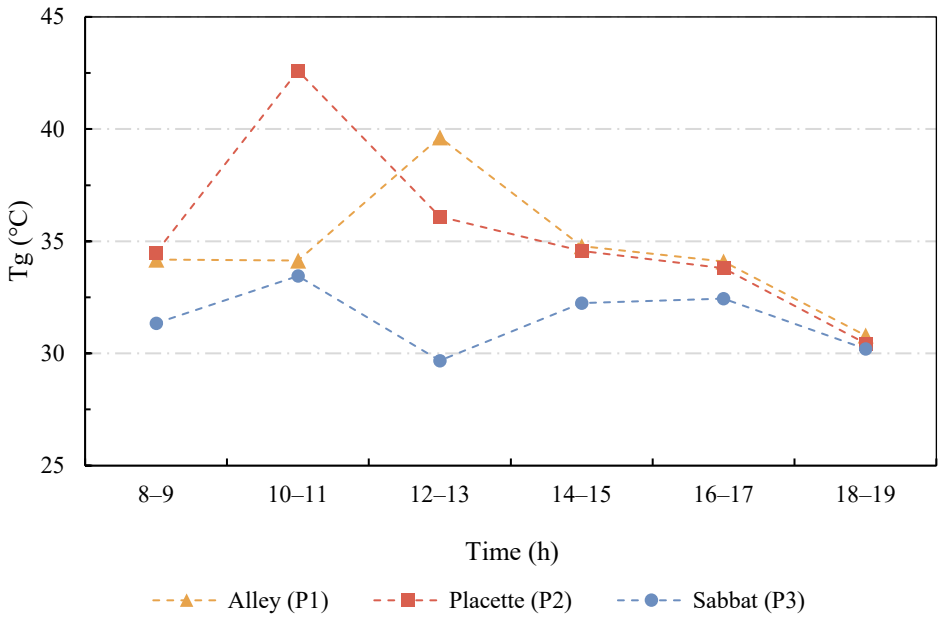


Figure 6. *Diurnal Variation of Globe Temperature across the Investigated Urban Typologies in the Medina of Tunis*
Source: Authors.

Radiative Heat Contribution

Figure 7 presents the difference between globe and air temperature (ΔTrad = Tg − Ta) as an indicator of the relative contribution of radiant conditions to the measured thermal environment. The exposed placette (P2) exhibited predominantly positive ΔTrad values, reaching a maximum of +4.13°C during the 10:00–11:00 period, although slightly negative values occurred during some later periods. In contrast, the sabbat (P3) exhibited negative ΔTrad values during several daytime periods, reaching a minimum of −3.88°C at 12:00–13:00, indicating that globe temperature was lower than the corresponding air temperature. The alley (P1) exhibited both positive and negative values across the measurement periods, showing greater temporal variability than the other two typologies. Overall, ΔTrad showed distinct spatial and temporal patterns across the three urban typologies, with the largest positive value recorded in the alley (+4.51°C at 08:00–09:00) and the largest negative value in the sabbat.

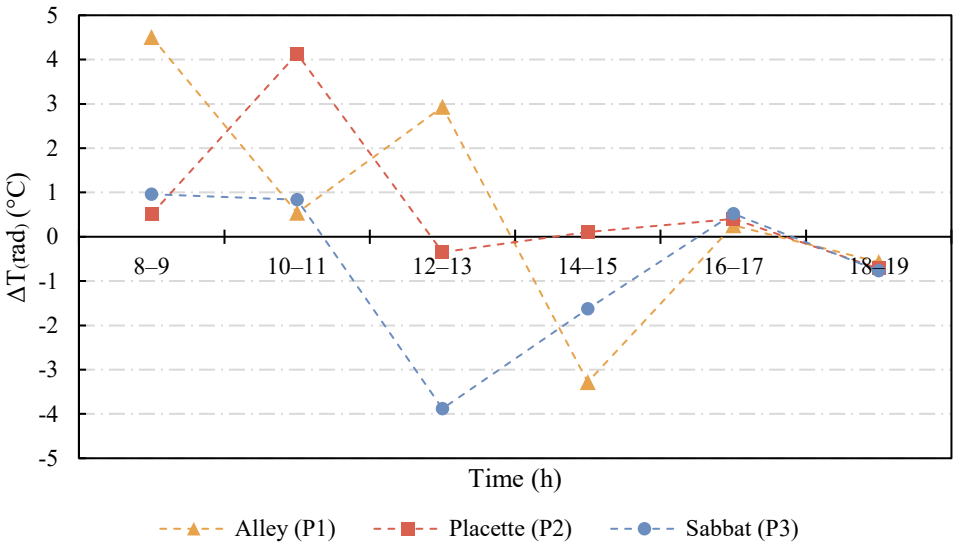


Figure 7. *Radiative Heat Contribution (ΔT(rad) = Tg − Ta) across the Investigated Urban Typologies in the Medina of Tunis. Positive values indicate increased radiative exposure, while negative values indicate reduced radiative exposure associated with shading and enclosure*
Source: Authors.

Thermal Attenuation and Spatial Enclosure

Table 3 summarizes the air-temperature differences between the exposed placette (P2) and the alley (P1) and sabbat (P3). The largest difference was observed between the placette and the sabbat during the 10:00–11:00 period (5.86°C), while the maximum difference between the placette and the alley reached 4.87°C during the same period. From 12:00 onward, the P2–P1 difference became negative, reaching −3.60°C at 14:00–15:00 as the alley became warmer than the placette. In contrast, the P2–P3 difference remained positive throughout the measurement periods and narrowed toward the evening, reaching 0.20°C at 18:00–19:00.

Table 3. *Air-Temperature Differences (ΔT, °C) between the Exposed Placette (P2) and the Alley (P1) and Sabbat (P3)*

Time	ΔT (P2–P1)	ΔT (P2–P3)
8–9	+4.32	+3.60
10–11	+4.87	+5.86
12–13	-0.25	+2.89
14–15	-3.60	+0.58
16–17	-0.44	+1.47
18–19	-0.20	+0.20

Source: Authors.

The peak conditions summarized in Table 4 further show that the placette recorded the highest peak Ta and Tg, whereas the sabbat exhibited the lowest peak values and considerably lower maximum positive ΔTrad.

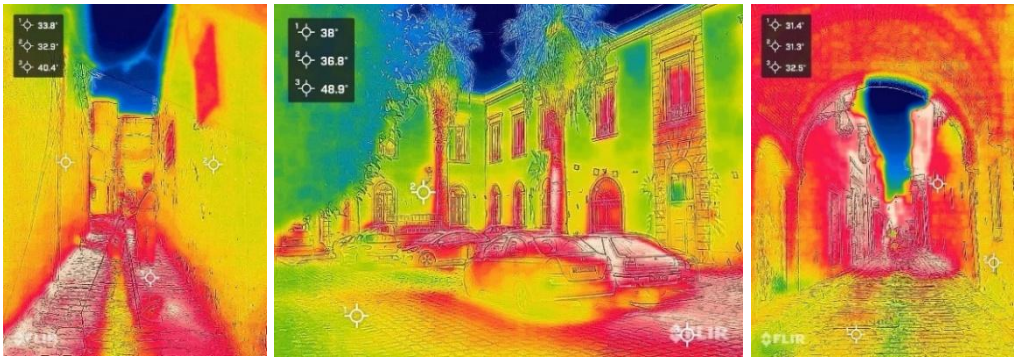
Table 4. *Summary of Peak Thermal Conditions across the Investigated Urban Typologies*

Urban Typology	Peak Ta (°C)	Peak Tg (°C)	Maximum ΔTrad (Tg − Ta) (°C)
Alley (P1)	38.06	39.63	+4.51
Placette (P2)	38.47	42.60	+4.13
Sabbat (P3)	33.88	33.45	+0.96

Source: Authors.

Surface Temperature Patterns and Thermal Buffering

Thermal imaging revealed pronounced spatial differences in surface temperatures among the three urban typologies during the afternoon measurement period (Figure 8). The exposed placette (P2) exhibited the highest surface temperatures, with directly sun-exposed elements reaching a maximum recorded Ts of 50.5°C. In contrast, surfaces within the sabbat (P3) remained considerably lower, generally between approximately 32 and 34°C, while the alley (P1) exhibited intermediate surface-temperature conditions. The thermal images also showed greater spatial heterogeneity in the placette, where exposed and shaded surfaces produced marked temperature contrasts, compared with the more uniform surface-temperature distribution observed within the sabbat.



(a) (b) (c)

Figure 8. *Representative Thermal Images Captured during the Afternoon Measurement Period (14:00–15:00) Showing Surface Temperature Distributions in the Three Urban Typologies: (a) Alley: Rue La Noria* (P1)*, (b) Placette: Palais Kheireddine* (P2)*, and (c) Sabbat: Rue du Pasha* (P3)
Source: Authors.

The surface-temperature measurements summarized in Table 5 further quantify these differences according to surface type and solar exposure during the 14:00–15:00 measurement round. Sun-exposed ground temperatures reached 46.1°C in the placette and 41.2°C in the alley, compared with shaded ground temperatures of 35.1°C and 34.9°C, respectively. Within the sabbat, where no directly sun-exposed ground or wall surfaces were recorded, shaded ground and wall temperatures remained at 32.4°C and 32.8°C, respectively, with a maximum recorded Ts of 34.0°C. Across the three typologies, the maximum recorded surface temperature therefore ranged from 50.5°C in the exposed placette to 34.0°C in the covered

sabbat, representing a difference of 16.5°C during the 14:00–15:00 measurement round. This contrast indicates that the strongest surface heating was associated with directly exposed surfaces, whereas the fully covered sabbat maintained substantially lower surface temperatures across the measured surfaces.

Table 5. *Maximum Recorded Surface Temperatures (Ts, °C) by Surface Exposure Condition across the Investigated Urban Typologies between 14:00 and 15:00 on 11 August 2025*

Surface Type	Alley (P1)	Placette (P2)	Sabbat (P3)
Sun-exposed ground surface Ts (°C)	41.2	46.1	N/A
Shaded ground surface Ts (°C)	34.9	35.1	32.4
Sun-exposed wall surface Ts (°C)	34.5	36.4	N/A
Shaded wall surface Ts (°C)	31.4	34.4	32.8
Maximum recorded Ts (°C)	41.2 (sun-exposed ground)	50.5 (sun-exposed door)	34.0 (roof)

Source: Authors.

Architectural Thermal Buffering and Spatial Sequence

Figure 9 illustrates the diurnal variation in air temperature across the spatial sequence of Dar Lasram. The Principal Patio, Skifa, Driba, and Conference Room are represented by measurements from 11 August 2025, while the Service Patio is represented by measurements from 18 August 2025, obtained during its separate monitoring period. The highest daytime maxima were recorded in the two patios, reaching 33.6°C in the Principal Patio and 33.0°C in the Service Patio.

In contrast, peak temperatures were lower in the transitional and enclosed spaces, reaching 31.1°C in the Skifa, 31.7°C in the Driba, and 31.9°C in the Conference Room.

The thermal profiles also show differences in the timing of these maxima. The Principal Patio reached its peak at approximately 11:50, while the Service Patio reached its peak at approximately 12:10.

Within the spatial sequence measured on 11 August, the Skifa and Driba reached their maxima at approximately 14:10, while the Conference Room peaked later, at approximately 15:40. Compared with the Principal Patio, the peaks in the Skifa and Driba were delayed by approximately 2 h 20 min and that of the Conference Room by 3 h 50 min, while their peak temperatures remained 1.7–2.5°C lower. Overall, the measured profiles show lower and progressively delayed daytime temperature peaks from the Principal Patio toward the transitional and enclosed spaces within the 11 August spatial sequence.

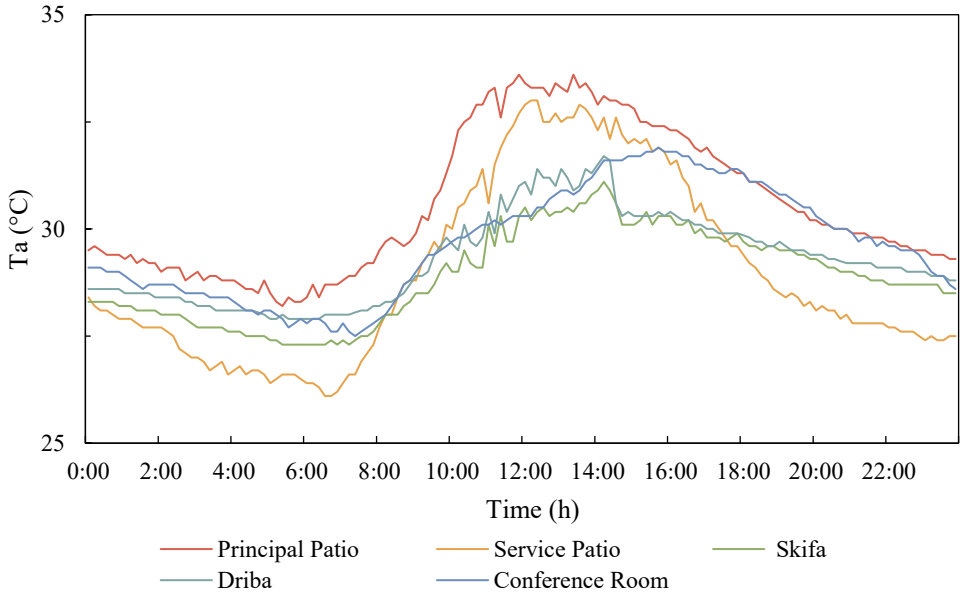


Figure 9. *Diurnal Air-Temperature Variation across the Spatial Sequence of Dar Lasram (Principal Patio, Skifa, Driba, and Conference Room: 11 August 2025; Service Patio: 18 August 2025)*
Source: Authors.

Urban Thermal Perception

The subjective survey responses showed distinct patterns in thermal sensation across the three urban spatial typologies (Figure 10). The placette (P2) generally exhibited the warmest thermal sensations, with TSV responses largely concentrated between slightly warm (+1), warm (+2), and hot (+3). The sabbat (P3) showed a clear temporal shift, from near-neutral to slightly cool sensations in the morning (mean TSV ≈ −0.3) to warmer sensations at midday (mean TSV ≈ +0.8), reaching its highest mean TSV in the evening (≈ +1.0).

The alley (P1) exhibited intermediate but more variable thermal sensations, with responses ranging from cool (−2) and slightly cool (−1) to warm (+2) and hot (+3) across the measurement periods. Figure 10 further shows that the warmest subjective responses were concentrated around midday, particularly in the placette, where responses ranged between warm and hot (TSV +2 to +3). In comparison, the sabbat maintained a lower mean TSV at midday (≈ +0.8) before increasing to approximately +1.0 in the evening.

The results indicate distinct patterns of thermal perception across the three urban typologies, with the warmest sensations in the placette during the morning and midday periods, greater temporal variability in the alley, and progressively warmer mean sensations in the sabbat from morning to evening, when it recorded the highest mean TSV of the three typologies (+1.0, compared with +0.8 in the placette and +0.3 in the alley).

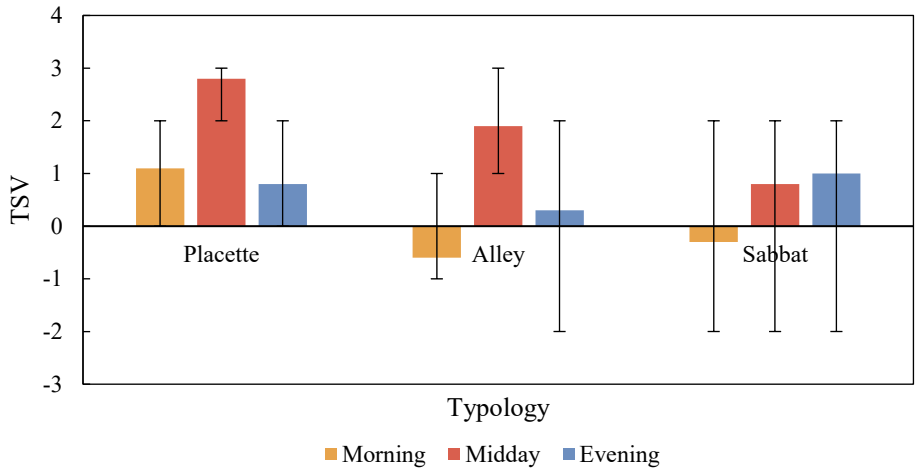


Figure 10. *Mean and Range of Thermal Sensation Vote (TSV) across the Three Urban Spatial Typologies and Time Periods in the Medina of Tunis. Error Bars Indicate the Observed Minimum–Maximum Range*
Source: Authors.

Thermal Perception across the Spatial Sequence and Adaptive Spatial Use

Figure 11 presents the mean Thermal Sensation Vote (TSV) and observed response range across the spatial typologies of Dar Lasram. The Principal and Service Patios exhibited the warmest thermal sensations, particularly at midday, with mean TSV values of +2.5 and +2.3, respectively. In contrast, the Skifa and Driba showed substantially cooler perceptions, with morning mean TSV values of −1.1 and −1.2 and midday values of +0.4 and +0.1, respectively. The Conference Room exhibited a mean TSV of −0.6 in the morning, increasing to +1.2 at midday before returning to +0.2 in the evening. Across the spatial sequence, the largest differences in mean TSV were therefore observed during the midday period, when the patios were perceived as warm to hot while the Skifa and Driba remained close to neutral.

Temporal differences were also evident across the three survey periods. Thermal sensations generally shifted toward warmer values from morning to midday, followed by lower mean TSV values in the evening in the interior spaces. Participants additionally reported adaptive behaviors during warmer periods, including movement toward shaded areas and preference for naturally ventilated transitional spaces. The results indicate comparatively moderated thermal sensations within transitional and enclosed spaces relative to the patios, together with temporal differences in thermal perception and reported spatial use.

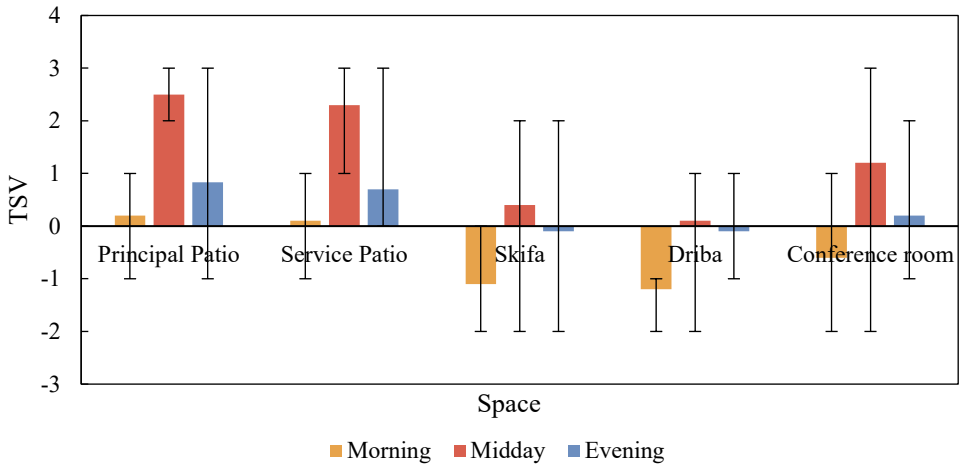


Figure 11. *Mean and Range of Thermal Sensation Vote (TSV) across Spaces and Time Periods in Dar Lasram. Error Bars Indicate the Observed Minimum–Maximum Range*
Source: Authors.

Discussion

The results indicate that radiative heat exchange, rather than air temperature alone, plays a major role in outdoor thermal stress within the Medina of Tunis. While variations in air temperature between spatial typologies remain relatively moderate, larger differences are observed in globe temperature and radiative heat contribution, highlighting the influence of solar exposure on thermal conditions.

The exposed placette exhibits the highest globe temperature during peak solar hours, consistent with its direct exposure, whereas the sabbat remains considerably moderated through shading and enclosure. From midday onward, however, the globe temperature of the alley exceeds that of the placette (Figure 6), with its radiative contribution also higher at 12:00–13:00 (Figure 7), likely influenced by localized tree shading within the placette (Table 1) limiting radiative gain after midday while the alley's canyon geometry admits direct sun once the solar angle aligns with its orientation.[27] The sabbat even shows negative radiative heat contribution in some periods, consistent with reduced exposure under its covered configuration. Overall, thermal exposure decreases progressively as enclosure and shading increase, with the alley behaving as an intermediate, transitional environment.

At the architectural scale, the thermal sequence observed in Dar Lasram further supports this buffering mechanism. The Principal Patio (partially covered) records the highest peak air temperature within the 11 August spatial sequence, while transitional spaces such as the Skifa and Driba maintain comparatively moderated thermal conditions. Although the Conference Room does not record the lowest peak air temperature, its delayed thermal response during the late afternoon suggests the influence of thermal inertia and heat storage within enclosed spaces. This indicates

27. Mihalakakou, Paravantis, Nikolaou, Malefaki, Romeos, Fotiadi, et al., "Urban Canyon Geometry and Green Infrastructure: A Review of Strategies for Enhancing Thermal Comfort and Microclimate," *Sustainability* 18, no. 9 (2026): 4335.

that thermal buffering within the courtyard house is achieved not only through reductions in peak temperature but also through the temporal moderation and stabilization of indoor thermal conditions.

The thermal perception results are consistent with the measured thermal sequence observed in Dar Lasram. The Conference Room exhibited an increase in perceived warmth at midday (mean TSV = +1.2), although thermal sensations remained lower than in the Principal and Service Patios (+2.5 and +2.3, respectively). Similarly, the Driba showed marginally cooler thermal sensations than the Skifa during the morning and midday periods. As the Driba recorded a slightly higher peak air temperature than the Skifa on 11 August (31.7°C and 31.1°C, respectively), this perceptual difference does not appear to be driven by air temperature alone and may be associated with their contrasting spatial configurations, particularly the larger vaulted volume of the Driba compared with the narrower, chicane-shaped configuration of the Skifa.[28] Given the sample size of the thermal perception survey (n = 30), these observations are presented as indicative perceptual trends.

The synthesis presented in Table 6 summarizes the relationship between spatial enclosure, solar exposure, and thermal stress across the investigated typologies. Across both scales, increasing spatial protection is associated with reduced solar exposure and thermal stress, although this pattern is less uniform within the courtyard house. Rather than functioning as isolated cooling elements, these spatial components therefore operate as an interconnected environmental sequence extending from the urban fabric to the interior spaces of courtyard houses.

Table 6. *Comparative Synthesis of Enclosure, Solar Exposure, and Thermal Stress across the Investigated Spatial Typologies*

Space	Enclosure	Solar Exposure	Thermal Stress
Placette	Open	High	High
Alley	Moderate	Moderate	Moderate
Sabbat	High	Low	Low
Patio (uncovered)	Open	High	High
Patio (partially covered)	Moderate	Moderate	High
Skifa/ Driba	High	Low	Low
Room	High	Low	Low

Source: Authors.

Across both scales, the TSV results indicate that participants perceive a corresponding thermal hierarchy. Exposed urban spaces such as the placette, as well as the patio spaces, are associated with warmer thermal sensations, whereas enclosed and transitional spaces including the sabbat, Skifa, and Driba are perceived as comparatively moderated environments during the morning and midday periods. The correspondence between environmental measurements and thermal perception suggests that spatial enclosure and shading influence thermal conditions not only through air-temperature moderation but also through reduced radiative exposure.

Figure 12 synthesizes this multi-scalar thermal regulation process, illustrating how enclosure, shading, and transitional spatial sequencing progressively moderate thermal

28. Revault, *Palais et demeures de Tunis: (XVIIIe et XIXe siècles)*, 1983.

stress from exposed urban environments toward buffered interior spaces. The mechanisms involved differ between scales. At the urban scale, thermal moderation is primarily associated with reductions in radiative exposure through shading and restricted sky view, as evidenced by the differences in globe temperature between the placette, alley, and sabbat. Within the courtyard house, the observed buffering effect appears more closely related to spatial transitions, enclosure, and thermal inertia, with the delayed response of the Conference Room illustrating the importance of temporal stabilization within the architectural sequence.

The findings have implications for contemporary climate-responsive design in Mediterranean environments. Rather than directly replicating historic forms, principles derived from the Medina may be reinterpreted through shaded pedestrian networks, reduced sky exposure, transitional semi-outdoor spaces, and spatial sequences that buffer environmental conditions before reaching occupied indoor areas. Such strategies may contribute to improved thermal conditions while maintaining architectural flexibility and contemporary design expression.

Thermal imagery and surface temperature observations provide additional evidence of the mechanisms underlying the measured microclimatic differences. The exposed placette exhibited higher surface temperatures and greater thermal heterogeneity than the alley and sabbat, particularly for directly sun-exposed surfaces. In contrast, the sabbat exhibited comparatively lower and more spatially uniform surface temperatures during the 14:00–15:00 measurement round. These observations support the measured reductions in globe temperature and thermal sensation reported in shaded and enclosed environments and further indicate the importance of limiting radiative heat gains through shading and enclosure.

The main contribution of this study lies in demonstrating that thermal buffering in the Medina operates across interconnected spatial scales rather than through isolated passive elements. By combining field measurements and thermal perception across both urban typologies and the internal spatial hierarchy of a courtyard house, the study identifies a continuous thermal sequence from exposed urban spaces to shaded passages, courtyards, transitional zones, and enclosed interiors. This multi-scalar perspective complements previous studies that have generally examined urban microclimate and building-scale thermal performance separately.

Although the present study primarily focuses on field-based environmental observations and thermal perception, the results suggest that spatial proportions, enclosure geometry, and material thermal inertia likely play important roles in shaping the observed thermal buffering mechanisms. Further simulation-based investigations may help quantify the influence of courtyard geometry, sky view factor, wall thermal mass, and spatial proportions on thermal performance within the Medina of Tunis.

Several limitations of this study should be acknowledged. First, urban environmental measurements were conducted using a rotational transect approach, yielding sequential rather than fully simultaneous observations across spatial typologies. As a result, short-term atmospheric fluctuations may have introduced variability in the observed differences between measurement locations. Similarly, at the architectural scale, the Service Patio was monitored during a subsequent period and was therefore not measured simultaneously with the main Dar Lasram spatial sequence, limiting direct temporal comparison. Second, the thermal

perception survey was based on a limited sample size (n = 30) and should therefore be regarded as exploratory rather than statistically representative of the broader Medina population. Future studies with larger samples and longer monitoring periods would help confirm these findings. Nevertheless, the consistency between instrumental measurements and thermal perception responses provides reasonable confidence in the interpretation of the spatial thermal buffering mechanisms observed within the Medina of Tunis.

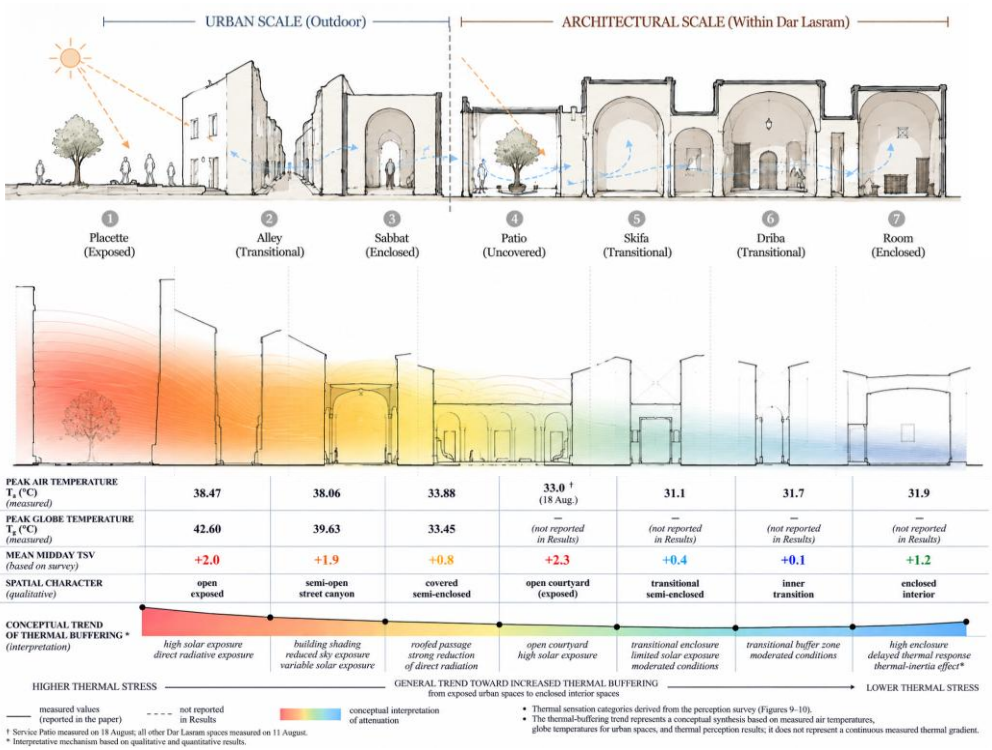


Figure 12. *Conceptual Model of Multi-Scalar Thermal Buffering in the Medina of Tunis Based on Environmental Measurements and Thermal Perception Analysis*
Source: Authors' illustration.

Conclusions

This study investigated how spatial configuration influences thermal conditions and thermal perception across interconnected urban and architectural scales within the Medina of Tunis. The results show that while air temperature differences between spaces remained relatively moderate, globe temperature and radiative heat contribution revealed substantial variations in thermal stress associated with solar exposure and spatial enclosure. The sabbat exhibited a globe-temperature reduction of 9.15°C compared with the exposed placette during the late-morning period, highlighting the substantial thermal contrast between exposed and covered urban configurations. The occurrence of negative radiative heat contribution values within the sabbat, reaching −3.88°C, further indicates reduced radiative exposure under its

covered configuration.

At the architectural scale, Dar Lasram exhibited lower and progressively delayed daytime temperature peaks from the Principal Patio toward transitional and enclosed spaces. Relative to the Principal Patio, peak temperatures in the Skifa and Driba were delayed by approximately 2 h 20 min and by 3 h 50 min in the Conference Room, while remaining 1.7–2.5°C lower. Thermal perception responses showed a corresponding spatial differentiation, with the warmest midday sensations reported in the Principal and Service Patios (mean TSV +2.5 and +2.3), while the Skifa and Driba remained closer to neutral (+0.4 and +0.1). These perceptual findings remain indicative given the exploratory sample size (n = 30). Together, these findings indicate that vernacular urban morphology and courtyard-house organization function as an integrated multi-scalar thermal buffering system, progressively moderating thermal stress from exposed urban spaces toward protected interior environments.

The findings highlight the contemporary relevance of these environmental principles, particularly shading, reduced radiative exposure, transitional spatial sequences, and progressive enclosure, for climate-responsive architecture and urban design in hot Mediterranean environments. The findings suggest that the thermal buffering capacity of the Medina lies not in any single passive element, but in the sequential organization of spaces with contrasting degrees of exposure, shading, and enclosure across urban and architectural scales.

Acknowledgments

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