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

This study investigates the role of vernacular spatial configuration in regulating thermal conditions at both urban and architectural scales within the historic Medina of Tunis. Through a multi-scalar analytical framework combining in-situ environmental measurements and thermal perception surveys, the research examines how traditional urban morphology and courtyard-house organisation contribute to passive cooling and thermal buffering in a hot-arid summer climate. Environmental measurements were conducted during the summer of 2025 across three representative urban typologies: an open placette, a narrow alley, and a covered passage (sabbat), as well as within Dar Lasram, a traditional courtyard house. Air temperature, relative humidity, air velocity, and globe temperature were recorded to characterise microclimatic conditions and assess radiative thermal stress. The results demonstrate that while air temperature differentials across typologies remain relatively modest, globe temperature exhibits substantial spatial variation. The exposed placette attained values exceeding 42°C, whereas the covered sabbat remained below 33.5°C, representing a reduction in radiative thermal stress of approximately 10°C. At the architectural scale, a progressive thermal attenuation gradient was observed from the open courtyard toward transitional and fully enclosed spaces. Thermal perception surveys corroborated these findings, confirming significantly higher thermal acceptability ratings in shaded and enclosed environments.

Keywords: *Urban Microclimate; Passive Cooling; Globe Temperature; Vernacular Architecture; Thermal Stress*

Introduction

The accelerating impacts of climate change, combined with rapid urbanization, are intensifying thermal stress in cities worldwide, particularly in Mediterranean and hot-arid regions, where rising temperatures, more frequent heatwaves, and amplified urban heat island effects are placing increasing pressure on built environments to ensure thermal comfort while minimizing energy consumption (UNESCO, 2025; UN-Habitat, 2024). In this context, the growing dependence on mechanical cooling systems is increasingly unsustainable, both environmentally and economically, prompting renewed interest in passive and low-energy architectural strategies.

Vernacular architecture, developed through long-term adaptation to local climatic conditions, offers valuable insights into climate-responsive design (D'amato & Kapoor, 2024). Among these, the historic fabric of the Medina of Tunis represents a compelling 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 (Benbrahim & Sriti, 2025). While its climatic responsiveness has been widely acknowledged in qualitative and historical studies, its quantitative evaluation across multiple spatial scales remains limited, particularly in linking urban morphology, environmental performance, and human experience (Pardo, 2023).

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 (Cherchi et al., 2025). 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, there is a lack of comprehensive frameworks capable of explaining how spatial configuration simultaneously influences environmental conditions and human experience (Liu et al., 2025). Dar Lasram, a well-preserved traditional courtyard house located within the Medina, was selected as a representative case study to examine thermal buffering mechanisms across the architectural spatial hierarchy.

To address this gap, this study investigates the Medina of Tunis as an integrated climate-responsive system. The research aims to evaluate how the spatial morphology of the Medina contributes to passive cooling and thermal comfort at both urban and architectural scales. Accordingly, the study is guided by the following research questions:

1. How do different spatial typologies (open urban nodes, shaded alleys, and courtyard environments) influence microclimatic conditions?
2. What passive cooling mechanisms explain the observed thermal variations across these spatial configurations?
3. How do occupants perceive and adapt to these microclimatic differences?

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, and air velocity across representative spatial typologies. These data are complemented by survey data capturing subjective comfort and adaptive practices.

By integrating environmental measurements and human-centred evaluation, this study investigates the Medina of Tunis as a multi-scalar climate-responsive system. 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, characterized by compact urban form, narrow shaded alleys, introverted courtyard houses, and transitional spatial sequences, reflects centuries of passive environmental adaptation to hot Mediterranean climatic conditions (Du, 2019). Traditional Islamic and North African architecture employs multiple passive cooling strategies through the deliberate manipulation of light, shadow, airflow, and enclosure (Abdalla & Yousif, 2025). Courtyards, arcades, and covered passages reduce radiative heat gain while stabilizing microclimatic conditions and improving natural ventilation (Zhou et al., 2025), and field investigations in comparable medinas such as the Algiers Casbah have confirmed measurable thermal comfort differences between enclosed and exposed environments (Arrar et al., 2022).

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 (Mihalakakou et al., 2026), with compact configurations and reduced SVF consistently linked to improved thermal comfort in historic urban fabrics (Lai et al., 2025). 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 (Racha & Kacher, 2020). These mechanisms are directly relevant to the Medina of Tunis, where compact morphology, shaded alleys, and covered passages such as the sabbat represent precisely the typologies identified in the literature as most effective for passive thermal regulation. The present study builds on this foundation by providing quantitative field-based evidence for their performance under contemporary summer conditions.

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 (Liu et al., 2025). 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 (Liu et al., 2025; Yahia et al., 2018). 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 (Arrar et al., 2022; Yao et al., 2025). While integrated indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) capture these combined effects (Liu et al., 2025), their predictive reliability is limited in naturally ventilated historic environments where occupants exhibit strong adaptive behavior and tolerance (Akbar Rahman, 2025). This body of evidence directly motivates the methodological choice in the present study to use globe temperature as the primary stress indicator and to complement physical measurements with a thermal perception survey capable of capturing occupant adaptation in the Medina of Tunis.

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 (Abdalla & Yousif, 2025). Through enclosure, shading, thermal mass, and spatial sequencing, courtyard-centered houses create buffered indoor environments capable of moderating short-term climatic fluctuations (Racha & Kacher, 2020). 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 (Racha & Kacher, 2020). These mechanisms are particularly significant in hot Mediterranean climates where reducing daytime radiative heat gain is essential for natural ventilation comfort (Yahia et al., 2018), and the performance of courtyard houses reflects the integrated relationship between geometry, materiality, enclosure, and spatial hierarchy rather than any single element. In the context of the Medina of Tunis, Dar Lasram offers an ideal case study to examine these mechanisms empirically: its well-preserved spatial sequence from uncovered patio through skifa, driba, and enclosed rooms provides a measurable thermal gradient that allows the buffering role of each transitional space to be isolated and evaluated.

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; radiative stress is best captured through globe temperature rather than 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 (Toparlar et al., 2017; Yu et al., 2025). 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/Materials and Methods

Research Framework

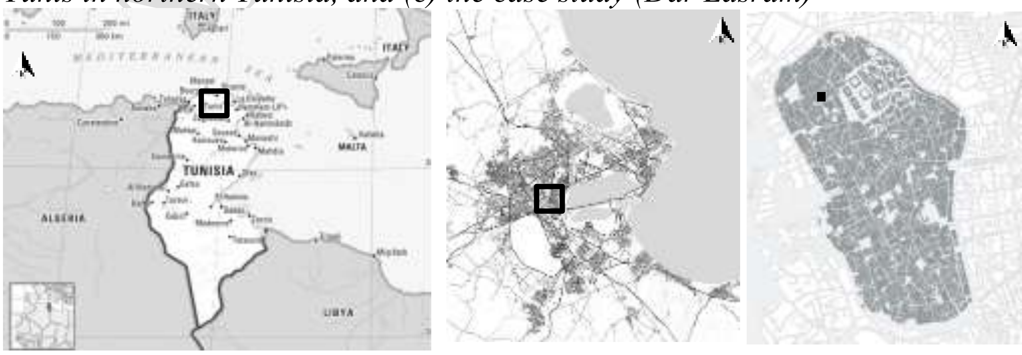
This study adopts a multi-scalar and interdisciplinary approach to investigate the passive cooling performance of the Medina of Tunis. The research framework integrates environmental measurement, and human-centred thermal perception to examine the relationships between urban morphology, microclimate,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

Field measurements capturing real environmental conditions across representative spatial typologies.
Thermal perception surveys to assess subjective comfort and adaptive behaviors.
This integrative approach enables the cross-comparison of physical data and human experience, bridging quantitative environmental performance and qualitative spatial perception.

Case Study Context

The study focuses on the historic Medina of Tunis, a dense and climate-responsive urban fabric characterized by compact morphology, irregular street networks, and courtyard-based residential typologies. Three representative spatial configurations were selected to reflect the diversity of microclimatic conditions and the hierarchical organization of the urban fabric: Open urban nodes (placettes and small squares) with higher solar exposure and increased sky view factors. Narrow shaded alleys (urban canyons) with reduced sky view factors and limited solar penetration. Introverted courtyards**,** functioning as semi-enclosed microclimatic regulators within residential structures. These typologies capture the thermal gradient from relatively exposed urban nodes to highly protected interior spaces, reflecting the spatial logic of the Medina.

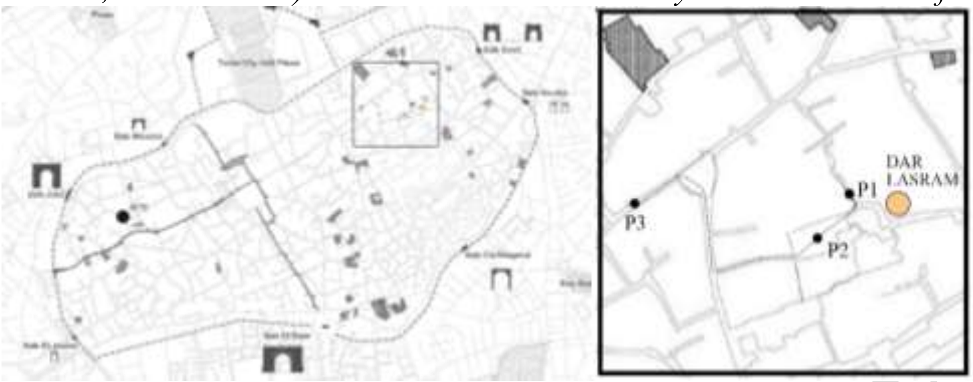
Figure 1. *Study area maps showing (a) Tunisia in North Africa, (b) the city of Tunis in northern Tunisia, and (c) the case study (Dar Lasram)*



a) b) c)

Source: Author.

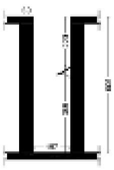
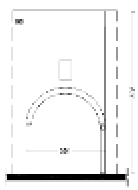
Figure 2. *Location of the investigated urban measurement points (P1 Alley, P2 Placette, and P3 Sabbat) and the Dar Lasram case study within the Medina of Tunis*



Source: Author.

Dar Lasram was selected as a representative courtyard house to examine thermal buffering mechanisms across the architectural spatial hierarchy, from semi-open and transitional spaces to enclosed interior rooms. In addition to its well-preserved architectural integrity, the building has undergone careful restoration and remains actively accessible to visitors and researchers, providing a valuable opportunity to investigate the environmental performance of a traditional courtyard-house typology under contemporary conditions.

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** Street “La Noria”	**P2 Placette** Place “ Palais Kheireddine”	**P3 Sabbat** Sabbat “Rue du Pasha”
Location map			
Represen-tative Section			

Site Photo			

Source: Author.

Figure 3. *(a) Site plan , (b) plan and (c) section of Dar Lasram*

a)

b)

c)
Source: Author.

Field Measurements

In-situ environmental measurements were conducted during the peak summer period (August 2025) to capture extreme thermal conditions under naturally ventilated scenarios.

The following parameters were recorded:

- Air temperature (Ta, °C)
- Relative humidity (RH, %)
- Air velocity (Va, m/s)
- Globe temperature (Tg, °C)
- Surface temperature (Ts, °C)

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), Kheireddine Palace (placette), and Sabbat Rue el Pasha. Representative Ts of ground surfaces, walls, doors, and shading elements were measured using an infrared thermometer and documented through thermal imagery to identify patterns of solar exposure, heat storage, and radiative cooling.

Measurements were taken at a standardized height of approximately 1.2 m above ground level, corresponding to pedestrian thermal exposure. Data were recorded at regular intervals to capture diurnal variations and peak heat conditions. Measurements were conducted using a rotational transect approach, resulting in sequential rather than strictly simultaneous observations across spatial typologies. In addition, reference data from a nearby meteorological station were used to contextualize local microclimatic variations.

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 during morning, midday, and evening periods to capture diurnal variations in microclimatic conditions across the urban spatial hierarchy.

Environmental parameters were measured sequentially across the selected urban typologies using a rotational transect approach. 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 the selected case-study building from 9 to 15 August 2025 to characterize indoor thermal behavior under real operating conditions within a historic courtyard house. Continuous on-site monitoring was performed to assess thermal and hygrothermal parameters relevant to occupant comfort in naturally ventilated 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 black globe thermometer with a diameter of 150 mm, in accordance with standard thermal comfort measurement practices. 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 entrance sequence (Driba and Skifa), two courtyards (Patio 1 and Patio 2), and an interior conference room. Outdoor environmental parameters air temperature, relative humidity, air velocity, and solar radiation were measured using the same ESPEC and Testo instruments**,** installed on the rooftop of a nearby building to capture local microclimatic conditions. A plan of the building indicating the measured spaces is presented in Figure 3.

Environmental monitoring was conducted over a seven-day field campaign during August 2025. For graphical presentation and comparative analysis, 11 August 2025 was selected as the representative day due to its clear-sky conditions and complete dataset availability across both urban and architectural monitoring locations. The results presented in Figures 5–12 therefore illustrate the thermal behavior of the investigated spatial typologies under representative peak summer conditions.

Thermal Perception Survey To incorporate the human dimension of thermal comfort, a preliminary occupant-based 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). Additional questions addressed thermal preference, perceived comfort, and adaptive behaviors such as movement toward shaded areas, clothing adjustment, and use of naturally ventilated spaces (Table 2).

Average TSV values were calculated for each spatial typology and time period to facilitate comparison between measured environmental conditions and subjective thermal perception.

A total of 30 participants were included in the thermal perception survey. The sample comprised both male and female respondents representing different age groups. To capture a diversity of thermal experiences and familiarity with the urban environment, the survey included both residents of the Medina of Tunis and non-residents. Participants were surveyed across different urban and architectural spatial typologies during morning, midday, and evening periods, enabling the assessment of thermal perception under varying environmental conditions.

Within Dar Lasram, thermal perception was evaluated across the principal patio, service patio, skifa, driba, and conference room in order to examine the relationship between measured environmental conditions and occupant perception within the courtyard-house spatial hierarchy. The survey was conducted concurrently with environmental measurements, enabling direct comparison between objective 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: Author.

Data Integration and Analysis

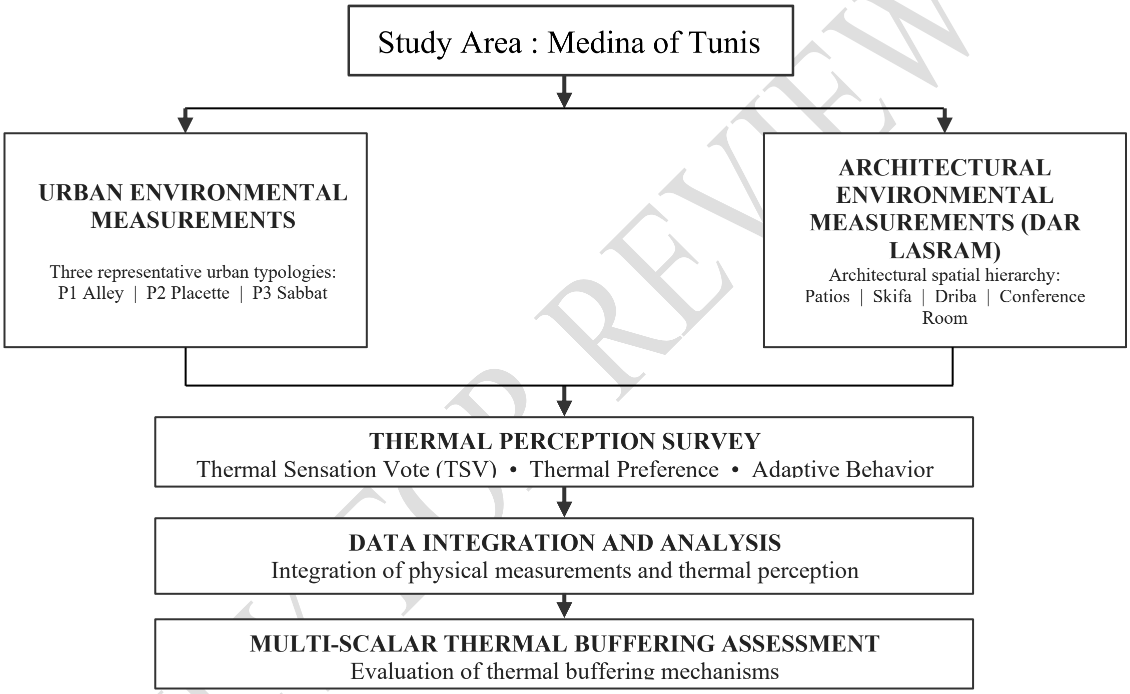
The datasets obtained from field measurements, and thermal perception surveys were analysed in an integrated framework to identify relationships between spatial configuration, environmental performance, and human experience.

Comparative analyses across spatial typologies were conducted to assess:

- Thermal attenuation between exposed and protected environments
- The cooling performance of courtyards as transitional spaces
- The relationship between measured environmental parameters and perceived comfort

This integrative methodology enables a holistic evaluation of passive cooling mechanisms, linking urban morphology, architectural space, and human adaptation. Figure 4 presents the methodological framework of the study, combining environmental measurements and thermal perception surveys to investigate thermal buffering mechanisms across multiple spatial scales.

Figure 4. *Methodological framework of the study*



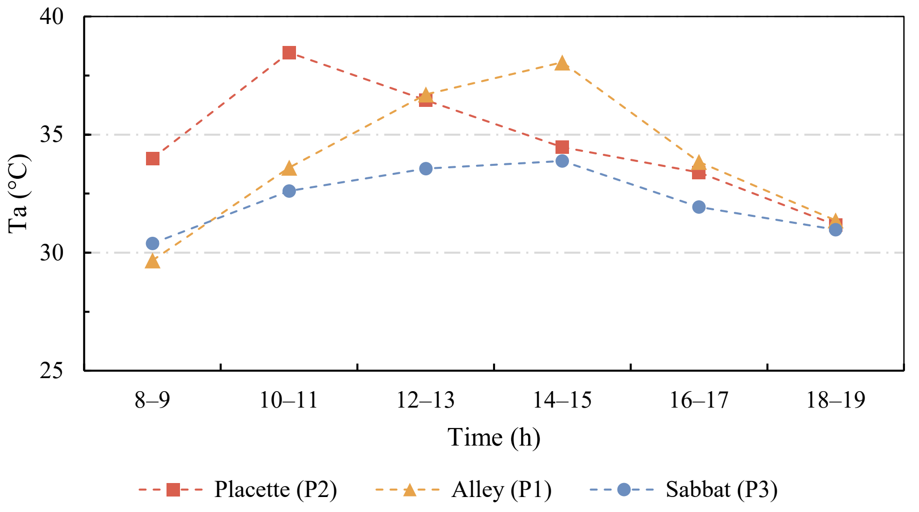
Source: Author.

Results

Air temperature variation across spatial typologies

Diurnal air temperature variations across the investigated spatial typologies remained relatively moderate, generally within a range of 2–6°C (Figure 5). The exposed placette consistently exhibited higher temperatures than the alley and sabbat, although the differences were comparatively small. These findings suggest that air temperature alone does not fully explain the thermal differentiation between urban spaces, highlighting the importance of examining radiative conditions through globe temperature and radiative heat contribution.

Figure 5. *Diurnal variation of Ta (°C) across spatial typologies in the Medina of Tunis. The exposed placette generally exhibits higher air temperatures, while the covered sabbat maintains comparatively lower values, reflecting the moderating effect of spatial enclosure*



Source: Author.

Radiative thermal stress (Globe temperature)

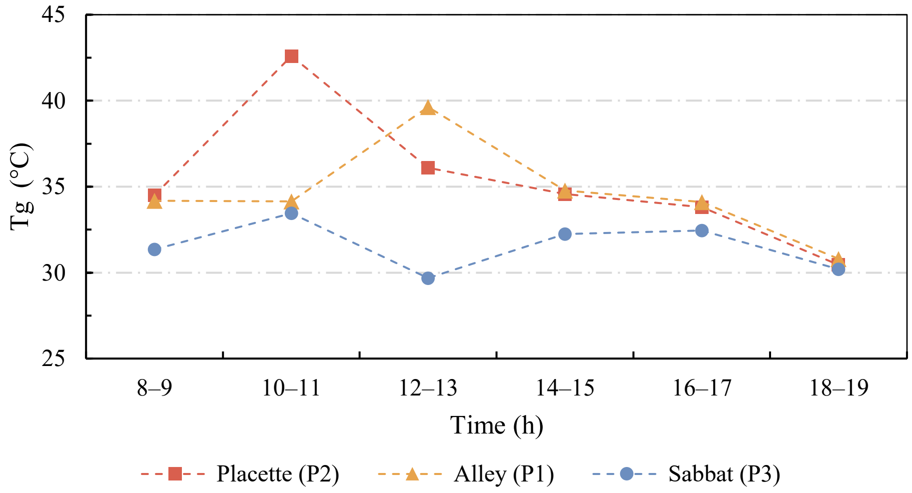
Figure 6 illustrates the variation of globe temperature, which reflects radiative heat exposure. Unlike air temperature, globe temperature shows significantly larger differences between spatial typologies.

The exposed placette reaches peak globe temperature values exceeding 42°C during late morning hours, while the sabbat remains below approximately 30–33°C during the same period. This indicates a substantial reduction in radiative thermal stress in enclosed spaces.

The alley again exhibits intermediate behavior, confirming its transitional role between exposed and protected environments.

These results highlight that radiative heat exposure, rather than air temperature alone, plays a dominant role in shaping outdoor thermal conditions across spatial typologies. This is further examined through the analysis of radiative heat contribution in the following section.

Figure 6. *Diurnal variation of globe temperature across spatial typologies in the Medina of Tunis. The exposed placette exhibits the highest radiative heat exposure, while the covered sabbat remains consistently cooler, reflecting the effect of spatial enclosure*

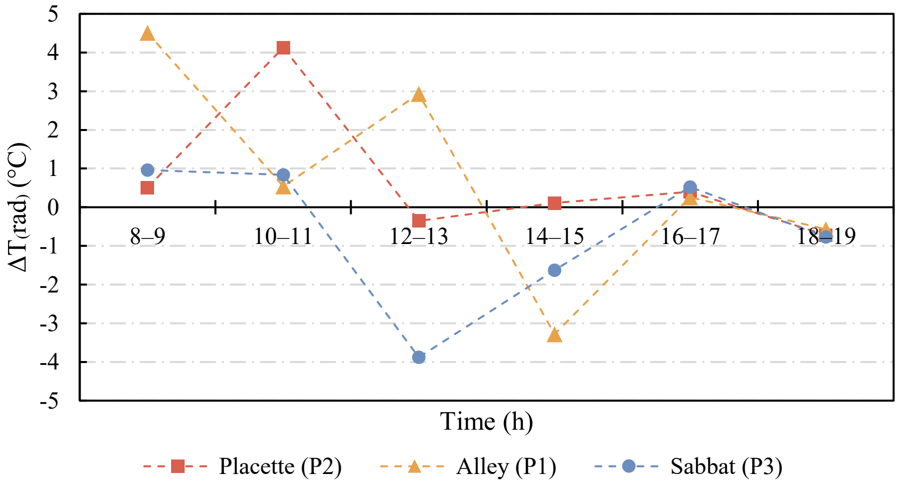


Source: Author.

Radiative heat contribution

Figure 7 illustrates the radiative heat contribution ($\Delta Trad = Tg - Ta$), providing a direct measure of radiative heat exchange. The exposed placette consistently exhibits positive values, indicating strong radiative heat gain due to direct solar exposure. In contrast, the sabbat (P3) exhibits negative values during peak periods ($\Delta Trad = Tg - Ta < 0$), indicating that globe temperature falls below the ambient air temperature. This behavior is attributed to the highly enclosed configuration of the sabbat, which substantially reduces direct solar radiation through overhead shading and restricted sky exposure. The absence of direct radiative gains, combined with the influence of shaded surrounding surfaces, results in a lower radiant environment and consequently reduced globe temperatures compared to the ambient air temperature. The alley exhibits mixed values, confirming its transitional role between exposed and enclosed environments. These findings demonstrate that differences in outdoor thermal conditions are primarily driven by radiative heat exchange rather than air temperature alone.

Figure 7. *Radiative heat contribution ($\Delta T_{(rad)} = Tg - Ta$) across spatial typologies in the Medina of Tunis. Positive values indicate increased radiative heat gain due to solar exposure, while negative values reflect effective radiative shielding in enclosed environments*



Source: Author.

Thermal attenuation and spatial enclosure

Table 3 presents the thermal attenuation observed between the exposed placette (P2) and the more sheltered urban typologies. The largest temperature difference was recorded between the placette and the covered sabbat (P3), reaching 5.86°C during the 10:00–11:00 period. In contrast, the maximum attenuation between the placette and the alley (P1) was 4.87°C. The attenuation effect was most pronounced during the late morning period and decreased during the afternoon as thermal conditions became more homogeneous across the urban fabric.

Table 3. *Thermal attenuation (ΔT, °C) between the exposed placette (P2) and the more sheltered urban typologies*

Time	ΔT (P2–P3)	ΔT (P2–P1)
8–9	3.6	4.32
10–11	5.86	4.87
12–13	2.89	-0.25
14–15	0.58	-3.6
16–17	1.47	-0.44
18–19	0.2	-0.2

Source: Author.

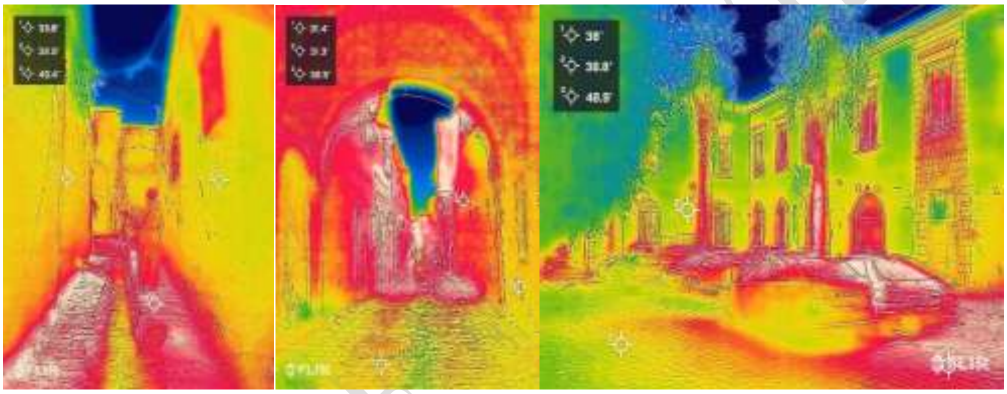
Table 4. *Summary of peak thermal conditions across the investigated urban typologies*

Urban Typology	Peak Ta (°C)	Peak Tg (°C)	Maximum ΔTrad (Tg − Ta) (°C)
Placette (P2)	38.47	42.60	4.13
Alley (P1)	38.06	39.63	4.51
Sabbat (P3)	33.88	33.45	−3.88

Source: Author.

Surface Temperature Patterns and Thermal Buffering

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) Rue La Noria, (b) Kheireddine Palace, and (c) Sabbat Ben Gacem*



(a) (b) (c)

Thermal imaging revealed substantial differences in surface temperatures among the three urban typologies. During the afternoon measurement period, the highest surface temperatures were observed in the exposed placette (Kheireddine Palace), where directly sun-exposed surfaces exceeded 50°C. In contrast, the covered sabbat exhibited significantly lower temperatures, with most measured surfaces remaining between approximately 32 and 34°C. Rue La Noria presented intermediate conditions due to its narrow geometry and partial shading. These observations indicate that urban shading configurations exert a stronger influence on radiative thermal conditions than on air temperature alone. The sabbat effectively reduced solar exposure and limited heat accumulation on surrounding surfaces, whereas the placette experienced substantial solar loading and surface heating. The thermal images therefore provide visual confirmation of the thermal buffering role of traditional shaded urban spaces within the Medina.

Table 5. *Representative Ts (°C) and Solar Exposure Conditions Across the Investigated Urban Typologies*

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)	31.4	36.4	N/A
Shaded wall surface Ts (°C)	34.5	34.4	32.8
Maximum recorded Ts (°C)	41.2	50.5	34.0

Table 5 summarizes representative surface temperatures extracted from the thermal imagery. The results reveal substantial differences between sun-exposed and shaded surfaces, particularly within the exposed placette where surface temperatures exceeded 50°C on directly irradiated elements. In contrast, surfaces within the covered sabbat generally remained between 32 and 34°C. The alley exhibited intermediate conditions. These findings indicate that shading and spatial enclosure substantially reduce surface heating and help explain the lower globe temperatures and thermal stress observed in the more protected urban typologies.

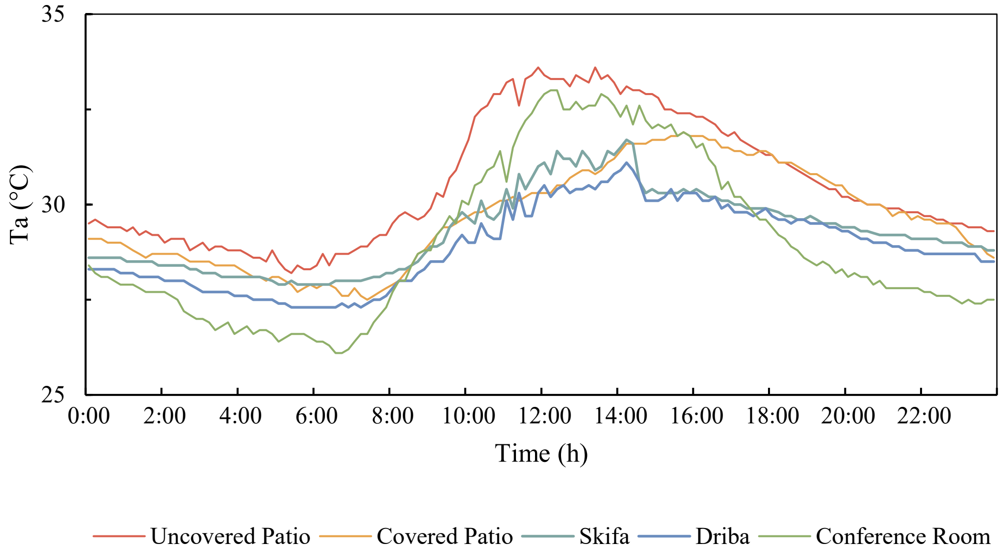
Architectural thermal buffering and spatial sequence

Figure 9 illustrates the diurnal thermal variation across the spatial sequence of Dar Lasram. A progressive attenuation of air temperature is observed from the uncovered courtyard toward deeper enclosed spaces. The uncovered patio exhibits the highest daytime temperatures, while the skifa and interior room maintain comparatively stable conditions throughout the day.

This thermal gradient highlights the buffering role of transitional spaces and enclosed configurations in regulating heat transfer and reducing thermal stress. The results suggest that the spatial hierarchy characteristic of traditional courtyard houses contributes to passive thermal moderation through progressive enclosure and controlled exposure.

In addition, the uncovered patio exhibits the strongest thermal fluctuations throughout the day, whereas transitional spaces such as the skifa and driba display smoother thermal profiles with reduced daytime peaks. The conference room demonstrates a delayed thermal response during the late afternoon period (approximately 16:00–18:00), remaining comparatively warm even as outdoor temperatures begin to decrease. This behavior suggests the influence of thermal inertia and delayed heat transfer within enclosed spaces.

Figure 9. *Diurnal air temperature variation across the spatial sequence of Dar Lasram. Progressive thermal attenuation is observed from exposed courtyard spaces toward enclosed interior environments, highlighting the buffering role of transitional spaces such as the skifa and driba*



Source: Author.

Urban thermal perception

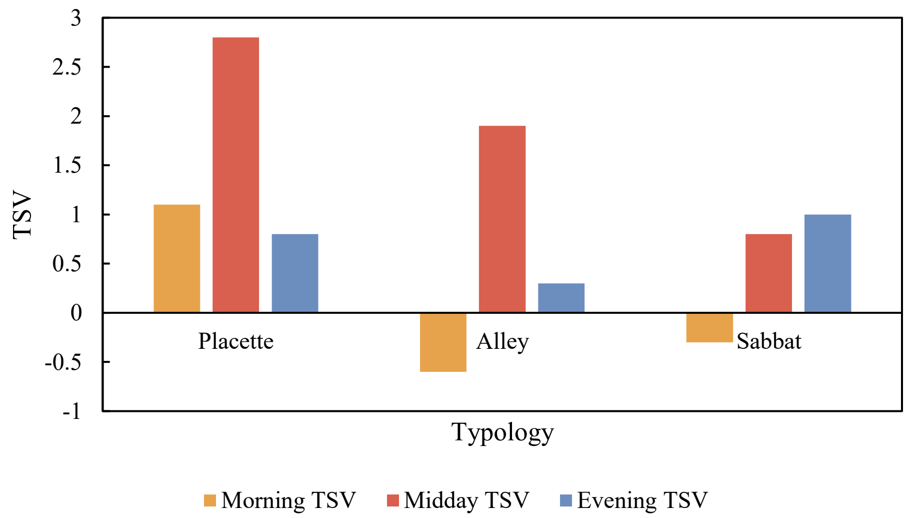
The subjective survey responses reveal clear differences in perceived thermal conditions across the urban spatial typologies of the Medina of Tunis. The placette generally exhibits the warmest thermal sensations, with TSV values largely concentrated between slightly warm (+1), warm (+2), and hot (+3), reflecting strong radiative exposure and direct solar exposure in open urban environments. In contrast, the sabbat maintains predominantly neutral to cool thermal sensations, with responses ranging from slightly cool (-1) and cool (-2) to neutral (0), indicating the moderating influence of shading, enclosure, and reduced radiative heat exposure.

The alley displays intermediate and highly variable TSV values, ranging from cool (-2) and slightly cool (-1) to warm (+2) and hot (+3), confirming its transitional thermal character between exposed and enclosed urban environments. This variability reflects fluctuating environmental conditions associated with partial shading, intermittent solar exposure, and intermediate enclosure conditions within the urban fabric.

Figure 10 further illustrates the evolution of average TSV values across morning, midday, and evening periods. Midday conditions correspond to the highest perceived thermal stress, particularly within exposed typologies such as the placette, whereas enclosed spaces such as the sabbat maintain comparatively moderated thermal sensations throughout the day. These subjective responses align with the measured differences in globe temperature and radiative heat contribution observed across the urban spatial hierarchy.

The placette exhibits the highest perceived thermal stress, particularly during midday periods, whereas the sabbat maintains comparatively moderated and cooler thermal sensations due to shading and enclosure. The alley displays intermediate TSV values, reflecting its transitional spatial condition between exposed and enclosed urban environments.

Figure 10. *Average TSV across urban spatial typologies and time periods in the Medina of Tunis*



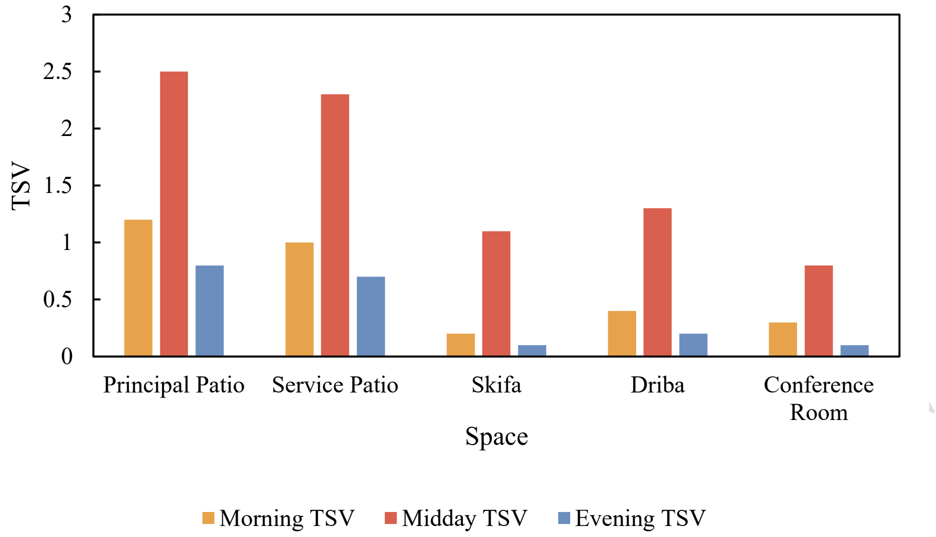
Source: Author.

Thermal perception across the spatial sequence and adaptive spatial use

The subjective survey responses reveal clear thermal differences across the spatial hierarchy of Dar Lasram. (Figure 11). The principal and service patios consistently receive warmer TSVs during midday periods, whereas the skifa and driba are perceived as comparatively cooler and more comfortable transitional environments. These perceptions support the measured thermal attenuation observed from exposed outdoor spaces toward buffered interior zones.

Semi-enclosed spaces such as the skifa and driba emerge as thermally preferable environments during hot periods due to shading, enclosure, and moderated airflow conditions. Several participants also reported adaptive behaviors including movement toward shaded areas and preference for naturally ventilated transitional spaces during periods of elevated thermal stress.

Figure 11. *Average Thermal TSV across spatial typologies and time periods in Dar Lasram*



Source: Author.

Figure 11 presents the average TSV across the spatial typologies of Dar Lasram during morning, midday, and evening periods. The principal and service patios show the highest TSV values, particularly during midday, indicating stronger perceived heat stress in exposed courtyard spaces. In contrast, the skifa, driba, and conference room show lower TSV values, suggesting more moderated thermal perception in transitional and enclosed spaces.

These subjective responses support the measured thermal sequence observed in Dar Lasram, where thermal conditions become progressively moderated from exposed courtyard areas toward buffered interior spaces.

Discussion

The results demonstrate that radiative heat exchange, rather than air temperature alone, governs outdoor thermal stress within the Medina of Tunis. While variations in air temperature between spatial typologies remain relatively moderate, substantially larger differences are observed in globe temperature and radiative heat contribution, highlighting the dominant influence of solar exposure on thermal perception.

The exposed placette exhibits the highest levels of radiative thermal stress due to direct solar exposure, whereas the sabbat maintains considerably moderated conditions through shading and enclosure. In some periods, the sabbat even displays negative radiative heat contribution values, indicating effective radiative shielding. These findings confirm the significant role of enclosed and semi-enclosed vernacular configurations in mitigating thermal stress within dense urban fabrics.

The alley behaves as an intermediate thermal environment, reflecting its transitional spatial condition between exposed and enclosed morphologies. This progressive thermal moderation across spatial typologies demonstrates that vernacular urban form operates as a passive environmental regulation system through controlled exposure, shading, and spatial sequencing.

At the architectural scale, the thermal sequence observed in Dar Lasram further supports this buffering mechanism. The uncovered patio exhibits the strongest thermal fluctuations, 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 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.

Together, the urban and architectural observations suggest that thermal moderation within the Medina of Tunis operates through a continuous spatial hierarchy extending from the urban fabric to the interior spaces of courtyard houses. At the urban scale, enclosed typologies such as alleys and sabbats reduce radiative heat exposure through shading and restricted sky view. At the architectural scale, transitional spaces including courtyards, skifas, and dribas further attenuate thermal fluctuations before heat reaches interior rooms. This multi-scalar spatial sequencing indicates that vernacular urban morphology and courtyard-house organization function not as isolated passive elements, but as interconnected environmental regulation systems that progressively buffer thermal stress through enclosure, shading, and controlled exposure.

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	Open	High	High
Skifa	High	Low	Low
Driba	Very high	Very low	Very low

Source: Author.

The synthesis presented in Table 6 suggests a clear relationship between increasing enclosure, reduced solar exposure, and decreasing thermal stress, highlighting the importance of spatial morphology in shaping microclimatic performance.

Rather than functioning as isolated cooling elements, the spatial components of the Medina operate as an interconnected environmental sequence. Thermal moderation begins at the urban scale through compact morphology, shaded circulation networks, and reduced sky exposure, before continuing at the architectural scale through courtyards, skifas, dribas, and thermally massive enclosures. This process creates a progressive thermal buffering effect in which environmental fluctuations are attenuated through successive spatial layers. The observed thermal gradient therefore reflects a hierarchical system of environmental regulation extending across multiple spatial scales.

The TSV results further indicate that occupants perceive this thermal hierarchy across both urban and architectural scales. Exposed urban spaces such as the placette, as well as uncovered courtyard areas, are associated with warmer thermal sensations, whereas enclosed and transitional spaces including sabbats, skifas, and dribas are perceived as comparatively moderated environments. These subjective responses align closely with the measured reductions in thermal exposure observed in shaded and enclosed spatial configurations. The correspondence between environmental measurements and occupant perception suggests that spatial enclosure and shading influence thermal comfort not only through temperature reduction but also through the moderation of radiative and environmental stress.

The results suggest that passive cooling within the Medina is fundamentally a spatial phenomenon. Rather than relying on technological interventions, thermal regulation emerges from the arrangement and sequencing of spaces with different levels of enclosure and exposure. The effectiveness of the system therefore depends not only on individual architectural elements but also on the relationships between them. This highlights the importance of considering vernacular settlements as integrated environmental systems rather than collections of isolated buildings.

Figure 12 synthesizes this multi-scalar thermal regulation process, illustrating how enclosure, shading, and transitional spatial sequencing progressively reduce radiative thermal stress from exposed urban environments toward buffered interior spaces. Such spatial strategies highlight the environmental potential of vernacular urban morphology and courtyard-house organization in moderating thermal stress through passive spatial configuration.

The synthesis further suggests that thermal buffering operates through different mechanisms at different spatial scales. At the urban scale, thermal moderation is primarily associated with reductions in radiative exposure achieved through shading and restricted sky view, as evidenced by the substantial differences in globe temperature between the placette, alley, and sabbat. Within the courtyard house, however, the observed buffering effect appears to be linked more closely to spatial transitions, enclosure, and thermal inertia. The conference room, despite not exhibiting the lowest peak air temperature, demonstrates a delayed thermal response relative to the transitional spaces, indicating that temporal stabilization constitutes an additional dimension of thermal buffering within the architectural sequence.

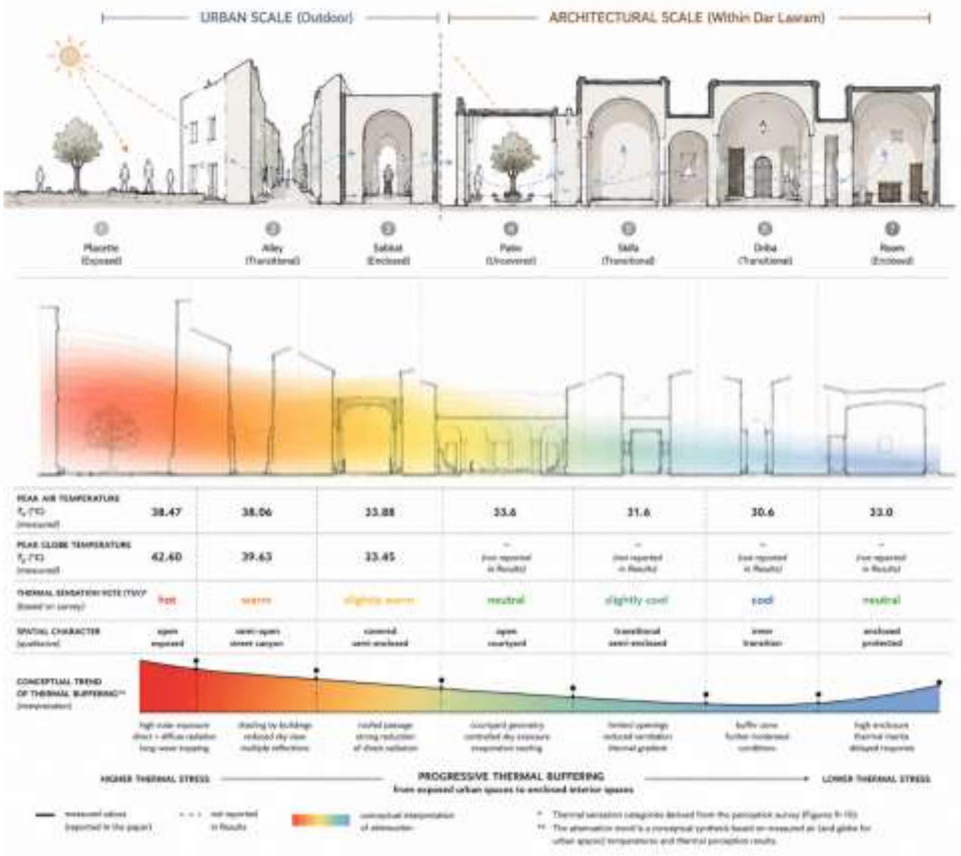
The findings suggest that the thermal performance of the Medina of Tunis is not solely the result of individual architectural elements, but rather of a hierarchical spatial organization that progressively moderates thermal stress through enclosure, shading, and transitional spaces. These principles may provide valuable guidance for contemporary climate-responsive design in Mediterranean environments. Rather than replicating historic forms directly, urban planners and architects may reinterpret these strategies through shaded pedestrian networks, reduced sky exposure, transitional semi-outdoor spaces, and spatial sequences that buffer environmental conditions before reaching occupied indoor areas. Such approaches may contribute to improved outdoor thermal comfort and reduced cooling demand while maintaining architectural flexibility and contemporary design expression.

Thermal imagery and surface temperature observations provided additional evidence of the spatial mechanisms underlying the measured microclimatic differences. The exposed placette exhibited substantially higher surface temperatures and greater thermal heterogeneity than the alley and sabbat, particularly during periods of intense solar exposure. In contrast, the covered sabbat maintained comparatively lower and more spatially uniform surface temperatures throughout the day. These observations support the measured reductions in globe temperature and thermal sensation reported in shaded and enclosed environments. The results suggest that the thermal performance of the investigated urban typologies is primarily associated with their capacity to limit radiative heat gains through shading and enclosure, thereby reducing surface heating and moderating the surrounding thermal environment.

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 a significant role 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, and the influence of transient microclimatic conditions cannot be entirely excluded. Second, the thermal perception survey was based on a limited sample size and should therefore be regarded as exploratory rather than statistically representative. Future studies employing larger participant cohorts and longitudinal monitoring would strengthen the generalisability of these findings. Nevertheless, the overall consistency between instrumental measurements and occupant thermal 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 Derived from Environmental Measurements and Thermal Perception Analysis*



Source: Author illustration.

Conclusions

This study investigated the influence of spatial typology on thermal conditions in the Medina of Tunis through field measurements and microclimatic analysis conducted across both urban and architectural scales.

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 covered sabbat exhibited reductions in radiative thermal stress of up to approximately 10°C compared with the exposed placette, highlighting the dominant influence of shading and enclosure on outdoor thermal conditions. The occurrence of negative radiative heat contribution values within the sabbat further demonstrates the effectiveness of vernacular urban morphology in mitigating radiative heat exposure.

At the architectural scale, the thermal sequence observed within Dar Lasram demonstrates progressive thermal attenuation from courtyard spaces toward enclosed interior environments. Transitional spaces such as the skifa and driba contribute to moderated thermal fluctuations, while interior rooms exhibit delayed thermal response associated with thermal inertia and heat storage effects.

Together, these findings demonstrate 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 study highlights the relevance of traditional environmental design principles for contemporary climate-responsive architecture and urban design, particularly in hot Mediterranean climates facing increasing thermal stress due to climate change.

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