



# Revealing walking experiences for shading based gendered perceptions of thermal comfort in a hot city

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## Abstract

Urban pedestrian environments shape subjective thermal comfort under intensifying heat stress; however, the pathway through which shading translates into walking experience remains insufficiently specified, particularly regarding potential gender heterogeneity. This study examines how perceived shade quality relates to subjective thermal perception, walking satisfaction, and duration of public-space use in Macau. A mixed-method design integrates climate-informed solar-access screening and on-site surveys, and Partial Least Squares Structural Equation Modelling is applied to test a perception-led mediation structure with female–male multi-group comparison. Results indicate that shade quality contributes to walking satisfaction primarily through subjective thermal perception, while duration-related effects are more contingent. Multi-group tests show that the core behavioural paths are statistically comparable across groups, whereas gender-sensitive differences are detected in the perceptual linkage between shade quality and subjective thermal perception and, more clearly, in the associations between subjective thermal perception and concurrent microclimatic indicators (relative humidity, air temperature, wind speed, and solar radiation). These findings support heat-responsive shading strategies that prioritise perceptual thermal relief through shade continuity while providing microclimatic options that accommodate heterogeneous regulation under hot-humid exposure.

**Keywords** Shade quality · Walking satisfaction · Subjective thermal comfort · Gender differences · Urban walking spaces

## Introduction

Heat exposure has become a central constraint on outdoor activity in many cities, where high radiant load and prolonged sun exposure increase health risks and reduce the

feasibility of spending time outdoors (Ebi et al. 2021; Guo et al. 2023, 2024; Hoehne et al. 2018; Z. Li et al. 2024a, b). These risks are pronounced in subtropical and tropical regions globally (Ebi et al. 2021; Li et al. 2024a, b; Turner et al. 2023; Zhang et al. 2019), and particularly in South China and Southeast Asia, where compact urban form, dense built surfaces, and restricted sky view factors intensify heat accumulation and limit natural shading (Emmanuel et al. 2007a, b; Lin and Matzarakis 2008b; Song et al. 2020; Tong et al. 2017). Walking remains a core component of everyday mobility and tourism in such contexts, supporting access to services, cultural engagement, and local economic activity (Kanellopoulou 2018; Karupiah and Bada, 2018; Sharipov and Demirkol 2018). Under rising temperatures, however, the quality of walking increasingly depends on the thermal conditions present along pedestrian routes, especially exposure to direct and reflected solar radiation (Azegami et al. 2023; Y. Li et al. 2023a, b).

Within this climate context, thermal comfort forms a key dimension of walking experience. Outdoor thermal comfort

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research has examined how air temperature, humidity, wind, and radiation collectively shape thermal sensation and acceptability in open spaces, and has shown that thermal conditions influence the presence, timing, and intensity of outdoor activities (Chen and Ng 2012; Z. Li et al. 2024a, b; Sofia Thorsson et al. 2007a, b). Studies on parks, streets, and squares indicate that pedestrians adjust route choice, timing, and duration of use in response to perceived heat and cooling opportunities (Z. Li et al. 2024a, b; Lin et al. 2013). This work has introduced subjective thermal perception as a central construct, showing that thermal sensation and comfort votes, rather than objective indices alone, are strongly associated with observed behaviour (Elnabawi et al. 2025; Z. Li et al. 2024a, b; Schweiker et al. 2017; Sofia Thorsson et al. 2007a, b; Yang et al. 2024). Yet, in many walking and tourism studies, thermal comfort still appears as a peripheral condition rather than an explicit determinant of walking satisfaction under heat.

Shading is a primary environmental factor influencing outdoor thermal comfort for pedestrians, because it modifies short-wave radiation and mean radiant temperature along walking routes (Berkovic et al. 2012; Y. Li et al. 2023a, b; Lin et al. 2025; Nasrollahi et al. 2021; Turner et al. 2023). Research on street trees, colonnades, and canopies has demonstrated that vegetation-based and building-based shading can reduce radiant exposure, lower physiological heat stress indices, and expand the set of conditions under which outdoor activity remains thermally acceptable (Ou and Lin 2023; Park et al. 2019; Sang et al. 2025). Numerical and field studies in hot cities indicate that shaded segments are more frequently used and that routes with higher shade fractions support longer activity duration during warm periods (Martinez et al. 2025; Melnikov et al. 2022; Nasrollahi et al. 2021; Peng et al. 2019; Shu et al. 2024). However, much of this work focuses on the presence or geometric proportion of shade and on physical cooling effects, with less attention to how pedestrians perceive different shading configurations, how these perceptions structure walking satisfaction, or how the quality and continuity of shading along a route are translated into behavioural responses.

Some research has related outdoor thermal comfort indices or thermal sensation votes to park attendance (Z. Li et al. 2024a, b; Zhang et al. 2019), street green affections (Park et al. 2019; Sang et al. 2025; Shu et al. 2024), route choice (Azegami et al. 2023; Melnikov et al. 2022; Moran et al. 2018), or time spent outdoors (Sang et al. 2025), while other work has evaluated how urban morphology and greenery influence pedestrian thermal environments (Guo et al. 2023; Li et al. 2024a, b; Taleghani et al. 2015; Tong et al. 2017). These studies show that more favourable thermal conditions are associated with higher reported comfort and increased outdoor presence, but typically do

not differentiate between the roles of shading quality, other microclimatic components, and subjective interpretation. In addition, many walkability frameworks in planning and transport research for walking environments more focused on connectivity, safety, and visual attributes (Angel et al. 2024; Mengiste et al. 2025; Shields et al. 2023), but less integrating thermal exposure or shade-related perception into models of walking. Therefore, there is limited theoretical integration that links shading conditions, subjective thermal perception, and walking experiences within a single explanatory framework, particularly in hot and humid high-density settings.

Demographic variation adds another layer of complexity to thermal experience. Studies on thermal comfort and environmental perception have reported differences in thermal sensitivity, preferred conditions, and affective responses across gender groups (Elnabawi et al. 2025; Hoehne et al. 2018; Jamei and Rajagopalan 2017). Evidence from outdoor and indoor settings indicates that these differences can influence thermal sensation votes, acceptability thresholds, and adaptation strategies, with implications for exposure and vulnerability (de Souza et al. 2024; Li et al. 2023a, b). However, most work treats gender as a background descriptor rather than explicitly examining how it conditions the pathways from environmental conditions through subjective thermal perception to adaptive behaviour. Few studies explicitly model how shading conditions are perceived by different gender groups, how subjective thermal perception mediates the influence of shade on walking-related outcomes, or whether these mediation processes vary by gender in hot urban environments.

These gaps indicate the need for an analytical approach that links urban shading, subjective thermal perception, and walking experiences in a way that can account for gendered differentiation under heat. The present study develops a perception-led and gender-sensitive framework to examine how shading quality shapes walking satisfaction of outdoor activities in hot Asian urban environments. Climatic data, microclimatic conditions, and shading characteristics are combined with survey-based measures of subjective thermal perception and walking experience, and Partial Least Squares Structural Equation Modelling is applied to test the pathways through which shading quality influences walking outcomes. By modelling subjective thermal perception as a mediator between shading quality and walking experience, and by estimating these relationships separately for female and male pedestrians, the study identifies group-specific perceptual and behavioural responses to heat. In doing so, the analysis responds to the urban heat issue by clarifying how shade configurations and perceptual processes jointly govern the capacity of pedestrians to sustain walking in thermally challenging environments.

## Literature review

### Indicators for analysis

Current scholars in biometeorology and outdoor thermal comfort have established that shading conditions and urban morphology shape pedestrian-level thermal exposure and thermal experience (Middel et al. 2016b; Nasrollahi et al. 2021), whereas walking-behaviour research has primarily examined how built-environment attributes relate to walking satisfaction and time spent in public space (Chan and Li 2022). However, these two streams remain only partially integrated, because shade quality and subjective thermal perception are frequently operationalised as contextual conditions or comfort outcomes rather than specified as mechanism variables that explain how built form becomes behaviourally consequential. Moreover, gender is often treated as a descriptive characteristic or covariate, even though perceptual interpretation and adaptive regulation under heat exposure may differ across gender groups, thereby motivating a gender-sensitive specification of indicator linkages and pathway structure.

Urban shading, provided primarily by buildings and vegetation, is widely acknowledged as an effective strategy for mitigating urban heat and improving thermal comfort (Emmanuel et al. 2007a, b; Lin et al. 2013; Tong et al. 2017). Studies have demonstrated the significant influence of shading on thermal perception and pedestrian behavior, often emphasizing the importance of analytical tools such as fisheye lens photography for sky view factor calculations (Hwang et al. 2011; Lin et al. 2013; Watanabe et al. 2014) and simulation models like ENVI-met and Ladybug (Aleksandrowicz et al. 2020; Evola et al. 2020). While these approaches have advanced shading assessments, they often neglect the social and spatial inequities in shading access, particularly in dense urban areas, where disparities in shade distribution may exacerbate thermal inequities (Middel et al. 2016a; Tan et al. 2017). Additionally, metrics such as sky view factors, while useful, may inadequately capture the broader impacts of shading on urban microclimates and pedestrian experiences, highlighting the need for more comprehensive evaluations (Ali-Toudert and Mayer 2006; Nasrollahi et al. 2021).

Walking satisfaction is typically conceptualised as an evaluative outcome shaped by comfort-related attributes and environmental experience, with thermal conditions constituting a salient determinant (Parsons 2007). Empirical work has reported that natural elements, including shading, are associated with improved walking evaluations and longer engagement in outdoor settings (Azegami et al. 2023; Djekic et al. 2018; Hwang et al. 2011). However, much of the literature focuses on thermal parameters

while underemphasizing the psychological and behavioral aspects of pedestrian experiences, such as adaptive preferences or the value placed on natural versus artificial shading elements (Jamei and Rajagopalan 2017). Consequently, the conditions under which shading ceases to yield measurable gains in walking satisfaction or duration remain insufficiently specified for context-sensitive intervention design, particularly when heterogeneity across pedestrian groups is not examined.

Subjective thermal perception integrates physiological, psychological, and contextual factors, providing a holistic measure of individuals' responses to thermal environments (Gagge et al. 1986; Schweiker et al. 2017). While established models such as the Predicted Mean Vote (PMV) and Standard Effective Temperature (SET) offer robust frameworks for assessing thermal comfort, their applicability is often constrained by assumptions that do not fully account for real-world environmental variability (Kong et al. 2019; Li et al. 2018; Parsons 2007; Yang et al. 2024). Studies have highlighted the dominant role of solar radiation in shaping thermal sensation, particularly in regions with high annual temperatures, but the interplay between radiation and other variables, such as wind and humidity, requires further exploration to ensure context-sensitive applications (Hirn et al. 2021; Lin et al. 2011; Tseliou et al. 2016). Therefore, a deeper integration of subjective thermal perception with urban design practices is essential to address the diverse thermal needs of urban populations (Bourbia and Bouch-eriba 2010; Stocco et al. 2015).

The built environment shapes both thermal conditions and walking behaviour through street scale, enclosure, material properties, and vegetation configuration (Kim et al. 2023; B. E. Saelens et al. 2003a, b). Factors such as street scale, building height-to-width ratios, and material reflectivity have been shown to mitigate urban heat and enhance thermal comfort (Jacobson and Ten Hoeve 2012; Rodríguez Algeciras et al. 2016; Rosso et al. 2018). However, the effectiveness of these interventions varies widely across urban contexts, underscoring the need for adaptable, localized strategies (Coutts et al. 2016; Morakinyo et al. 2018; Tan et al. 2017). The integration of natural elements, such as trees, within the built environment is particularly important for enhancing shading quality and pedestrian satisfaction. Research highlights the combined effects of urban canyon geometry and vegetation in optimizing thermal environments, although these interactions remain underexplored in diverse urban contexts (Hosseini et al. 2017; Jihad and Tahiri 2016; Nasrollahi et al. 2021).

Prior studies support individual relationships among shading, thermal perception, built-environment conditions, and walking outcomes; however, recent biometeorology and outdoor thermal comfort scholars have rarely specified an

integrated pathway linking shade quality to walking satisfaction and duration through subjective thermal perception, while walking-behaviour studies have often treated thermal perception and shade conditions as contextual background rather than mediation mechanisms. Moreover, despite frequent acknowledgement of gender differences in thermal experience, gender-sensitive divergence is seldom theorised within the mechanism structure that connects built environment and shading to evaluation and behavioural outcomes. Therefore, indicator selection and relationship specification in the present study are oriented toward an integrated, perception-led pathway, with explicit attention to whether perceptual and behavioural translation differs between females and males. Details of the operational indicators and supporting evidence are summarised in Table C1 (see supplementary material, SM).

### Conceptual linkages

Gender-differentiated walking outcomes under heat exposure are conceptualised through a perception-led pathway linking the built environment, shade quality, subjective thermal perception, walking satisfaction, and duration of public-space use (Table C2 in SM). In the outdoor thermal comfort and urban microclimate literature, the built environment is consistently treated as the primary spatial condition shaping shading formation and pedestrian-level thermal load (Jacobson and Ten Hoeve 2012; Kim et al. 2023; Rodríguez-Algeciras et al. 2018; Rosso et al. 2018; Brian E Saelens et al. 2003a, b). Street geometry, orientation, and enclosure affect radiation exposure and thermal conditions within street canyons, thereby influencing the presence and effectiveness of shade (Ali-Toudert and Mayer 2006; Nasrollahi et al. 2021; Sun et al. 2017). Moreover, built-form characteristics such as height–width relationships and spatial configuration influence the distribution and continuity of shading opportunities along walking routes, which is relevant for understanding how environmental exposure becomes behaviourally meaningful (Hosseini et al. 2017; Jihad and Tahiri 2016; Moran et al. 2018; Ruiz et al. 2017). However, behavioural implications are not assumed to be uniform across gender groups, because the translation from environmental conditions to walking outcomes is expected to depend on perceptual interpretation and adaptive regulation rather than on exposure alone (Jin et al. 2020; Tung et al. 2014).

Shade quality is therefore positioned as an intermediary that connects built form to subjective experience, while subjective thermal perception is treated as the central mechanism that converts shading conditions into evaluative and behavioural responses. Empirical evidence indicates that shading reduces radiant load and improves perceived

thermal conditions, particularly by lowering radiation exposure and mean radiant temperature (Rohinton Emmanuel et al. 2007a, b; Y. Li et al. 2023a, b; Lin et al. 2013; Ou and Lin 2023; Tong et al. 2017; Turner et al. 2023). Meanwhile, simulation-based studies have shown that built-environment design can substantially influence thermal comfort, reinforcing the need to link morphology and shading conditions to perceived experience rather than to rely on physical indicators alone (Ali-Toudert and Mayer 2006; Jamei and Rajagopalan 2017; Nasrollahi et al. 2021). Nevertheless, subjective thermal perception integrates perceived temperature, humidity, wind, and solar radiation into an overall thermal assessment, and this integrative process provides the proximate basis for environmental evaluation (Parsons 2007; Sofia Thorsson et al. 2007a, b). Consequently, identical shading conditions may not generate equivalent perceptual outcomes across gender groups if thermal sensitivity, perceptual thresholds, or interpretive consistency differ systematically (Greenfield et al. 2023; Jin et al. 2020; Tung et al. 2014).

The downstream outcomes of this pathway are supported by evidence that perceived thermal conditions shape walking satisfaction and outdoor engagement. Thermal comfort has been identified as a determinant of behavioural preference and outdoor use, indicating that perceived acceptability and neutrality contribute to favourable evaluations of walking environments (Lin and Matzarakis 2008a; Nikolopoulou and Lykoudis 2006). Moreover, thermal comfort has been associated with pedestrian frequency and longer periods of outdoor activity, linking perceived conditions to both satisfaction and use (Chen and Ng 2012; Klemm et al. 2015; Lin and Matzarakis 2008a). In addition, perceived thermal conditions have been shown to influence affective evaluation of outdoor settings, supporting the role of subjective perception in shaping satisfaction judgements (Knez and Thorsson 2008). At the behavioural level, reviews of outdoor thermal comfort research indicate that thermal conditions affect outdoor activity patterns and duration of stay (Chen and Ng 2012), while street greenery studies also report associations between improved thermal perception and behavioural willingness to remain outdoors (Klemm et al. 2015; Lin et al. 2013; Tong et al. 2017). Furthermore, walking satisfaction has been linked to longer time spent in public environments and outdoor engagement, supporting a sequential relationship from evaluative appraisal to duration outcomes (Friman et al. 2017; Shoval et al. 2018). However, the stability of the perceptual-to-evaluative and evaluative-to-behavioural translation is not presumed to be identical across gender groups, because adaptive strategies and decision processes under heat stress may differ (Tung et al. 2014; Wang et al. 2025). Therefore, the conceptual structure specifies a priori that built-environment conditions

shape shade quality, shade quality shapes subjective thermal perception, and perceived thermal conditions influence walking satisfaction and duration, while gender-sensitive divergence is expected primarily along the perceptual and behavioural translation segments. This theory-guided pathway motivates planned multi-group structural analysis to evaluate whether the magnitude and coherence of these relationships differ between female and male pedestrians.

## Methodology

### Research design

This study extends walkability research by integrating shade quality and subjective thermal perception into a climate-sensitive model of walking experience in Macau, building on the conceptual scope of (Ewing and Handy 2009). However, the target contribution concerns an indirect, perception-led mechanism and gender-contingent pathway differences rather than isolated associations; therefore, a modelling approach that estimates latent constructs and indirect effects while enabling formal multi-group comparison is required. Moreover, this specification provides a clearer evidentiary basis than single-equation regression with interaction terms or reliance on comfort indices alone, because mediated pathways and measurement error are addressed within one coherent structure. Phase 1 synthesised literature to define indicators and hypotheses. Phase 2 analysed climatic conditions during the investigation period and visualised daily thermal patterns using Python. Phase 3 conducted Ladybug screening simulations to identify peak solar-exposure periods and typology-level shade patterns to support survey timing and site-context interpretation, rather than to generate observed inputs for SEM estimation. Phase 4 implemented on-site surveys measuring shade quality, subjective thermal perception, walking satisfaction, and duration of public-space use. Partial Least Squares Structural Equation Modelling was then used to test the mediation structure and evaluate group differences.

### Study sites selection

Macau, characterized by high population density, narrow streets, and limited green spaces, faces unique microclimatic challenges that exacerbate thermal discomfort in its warm and humid climate. These conditions necessitate effective shading strategies to enhance thermal comfort, particularly in pedestrian-focused urban spaces. This study focuses on the Macau Peninsula, identifying four representative types of urban spaces to analyse the relationships between built form characteristics, shading patterns, and sun exposure

(Figure B2 in SM). In details, the selection of these space types ensures comprehensive coverage of Macau's urban spatial configurations and facilitates detailed investigation into shading's role in mitigating thermal discomfort. These analyses guided the determination of optimal data collection times, emphasizing periods of peak solar radiation to capture critical conditions affecting subjective thermal perception and walking satisfaction; simulation outputs were used for sampling justification and typology description rather than as observed SEM indicators. By focusing on these representative urban spaces, the study establishes a robust framework for examining the interplay between shading interventions and pedestrian experiences.

### Survey design

The survey design is structured to evaluate the relationships between the built environment, shade quality, subjective thermal perception, walking satisfaction, and duration of use in Macau's public spaces. The survey employed a 7-point Likert scale, ranging from -3 (lowest rating) to +3 (highest rating), to capture participants' perceptions across these dimensions.

Indicators for the survey were developed based on literature review (Table C1 in SM), where shade quality was assessed through green and building shade indicators, which have been shown to enhance thermal comfort and reduce heat stress. Subjective thermal perception was measured using variables like perceived wind speed, temperature, humidity, and solar radiation, reflecting individuals' nuanced experiences of urban thermal conditions. Walking satisfaction and duration of use were included to evaluate the behavioral and psychological impacts of the built environment and shading quality. The survey was administered in Chinese to ensure clarity and accessibility for participants.

### Sampling and data collection

A pilot test was conducted in early January 2023 to validate the survey's clarity and effectiveness. This phase involved a sample of 35 participants and was carried out during daytime hours, including both weekdays and weekends. Feedback from the pilot test ensured that the final questionnaire was fully understandable and ready for data collection.

The official data collection occurred from middle January to late June 2023, which covers both cool and hot season across the Macau Peninsula. Within each spatial typology (Figure B2 in SM), a random sampling strategy was employed. Participants were intercepted systematically at random intervals across multiple days and time slots between 11:00 AM and 1:00 PM, corresponding to peak thermal exposure, as these hours were identified through

simulation-based shading and sun-exposure analysis (Fig. 1 and Section A1 in SM) This temporal focus ensures that the collected data reflect critical thermal comfort conditions and provide a robust basis for subsequent analyses.

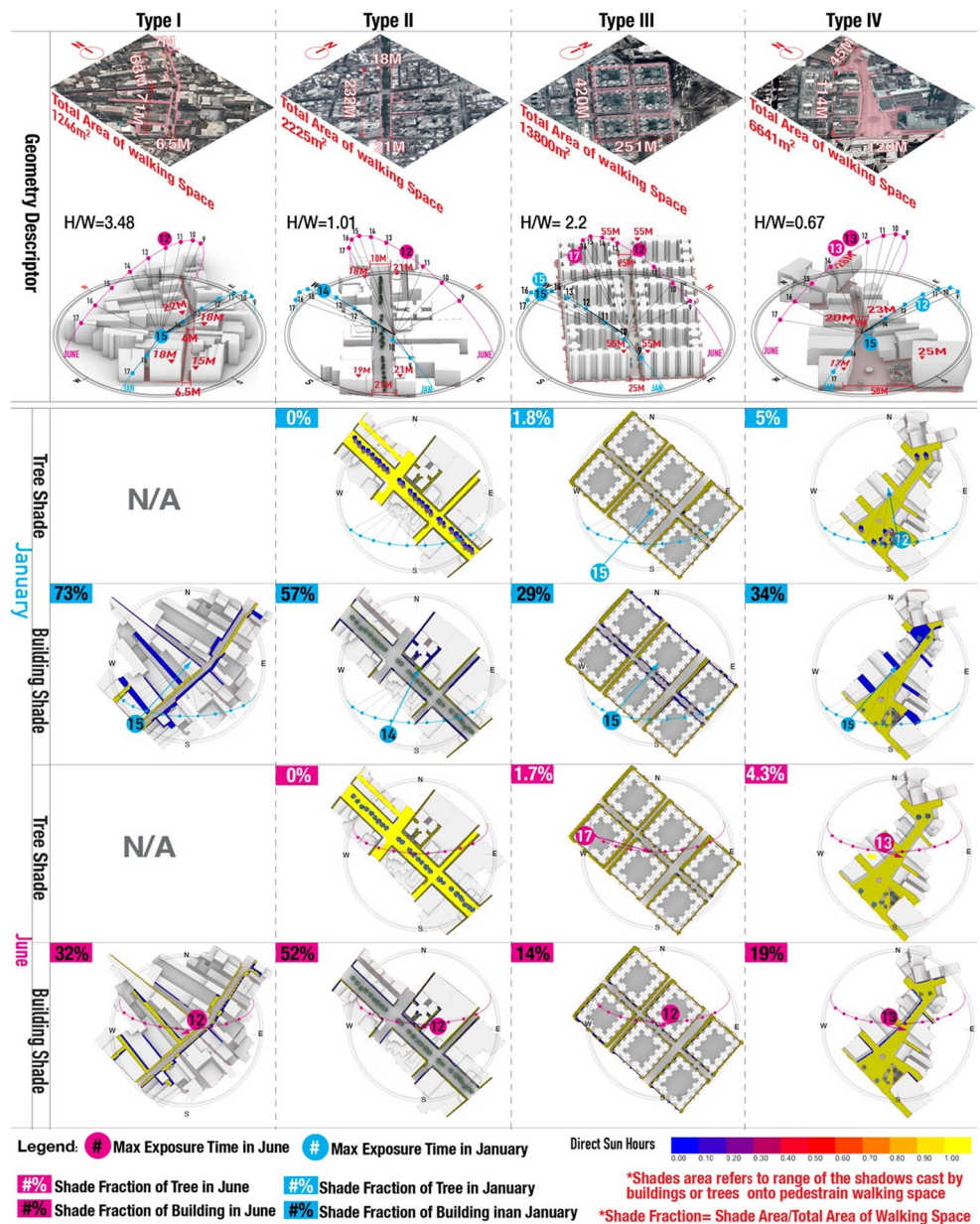
During the data collection process, a total of 3415 questionnaires were gathered, reflecting the efforts to reach a broad spectrum of participants through the sampling method. After data cleaning, 115 responses were excluded because respondent-level response variability was low (standard deviation across the full Likert-item battery < 0.3), indicating near-invariant/non-differentiated answering patterns (Curran 2016). The final dataset comprised 3300 valid responses with 39% male and 61% female (participants details refer to Section A2 in SM).

While inferential statistical models are used to analyze relationships between environmental features and pedestrian responses, we note that these are valid within the sampled population, defined by the spatially stratified random sampling frame. In line with recent methodological guidance (Hirschauer et al. 2020), we recognize the importance of probabilistic sampling when interpreting p-values and confirm that our design meets the assumptions for meaningful inferential testing.

### Conceptual model and analysis processes

The analysis integrates climatic data assessment and simulation screening with PLS-SEM. From a physical perspective, climatic data from the Macao Meteorological and

**Fig. 1** Shading conditions and solar exposure across types of urban spaces in Macau



Geophysical Bureau were analysed in Python to characterise investigation-period variation in temperature, relative humidity, solar radiation, and wind speed. Simulation analysis was conducted using Ladybug (version 1.7.26) in Rhino (version 8) with EPW input to screen peak solar-exposure periods and typology-level shade conditions. This screening informed the scheduling of on-site data collection and ensured that subjective perception measures were captured under verified thermal-stress conditions shaped by built form and greenery.

From a human-perception perspective, PLS-SEM was employed to examine relationships among the built environment, shade quality, subjective thermal perception, and pedestrian outcomes. SmartPLS (version 4.0) was used because it supports mediation testing, models incorporating formative and reflective constructs, and multi-group comparison. The model includes direct and mediated paths, with subjective thermal perception specified as the central mediator linking shade-related conditions to walking satisfaction and duration of use. Consistent with the study objective, the specification prioritises mechanism estimation under a standardised exposure window; therefore, age is included as a parsimonious control, whereas additional behavioural-context variables are treated as secondary determinants beyond the mechanism-focused scope. Simulation results were used to support the sampling window and typology context, whereas SEM estimation used survey-based latent constructs and observed indicators derived from the questionnaire.

The analytical framework is reflected in the theoretical model structure (Figure B4 in SM), which specifies directional paths among Built Environment (BE), Shade Quality (SQ), Subjective Thermal Perception (STP), Walking Satisfaction (WS), and Duration of Using Public Space (Du), enabling direct, indirect, and group-comparative evaluation of the perception-led pathway.

## Thermal climate and shade conditions in macau

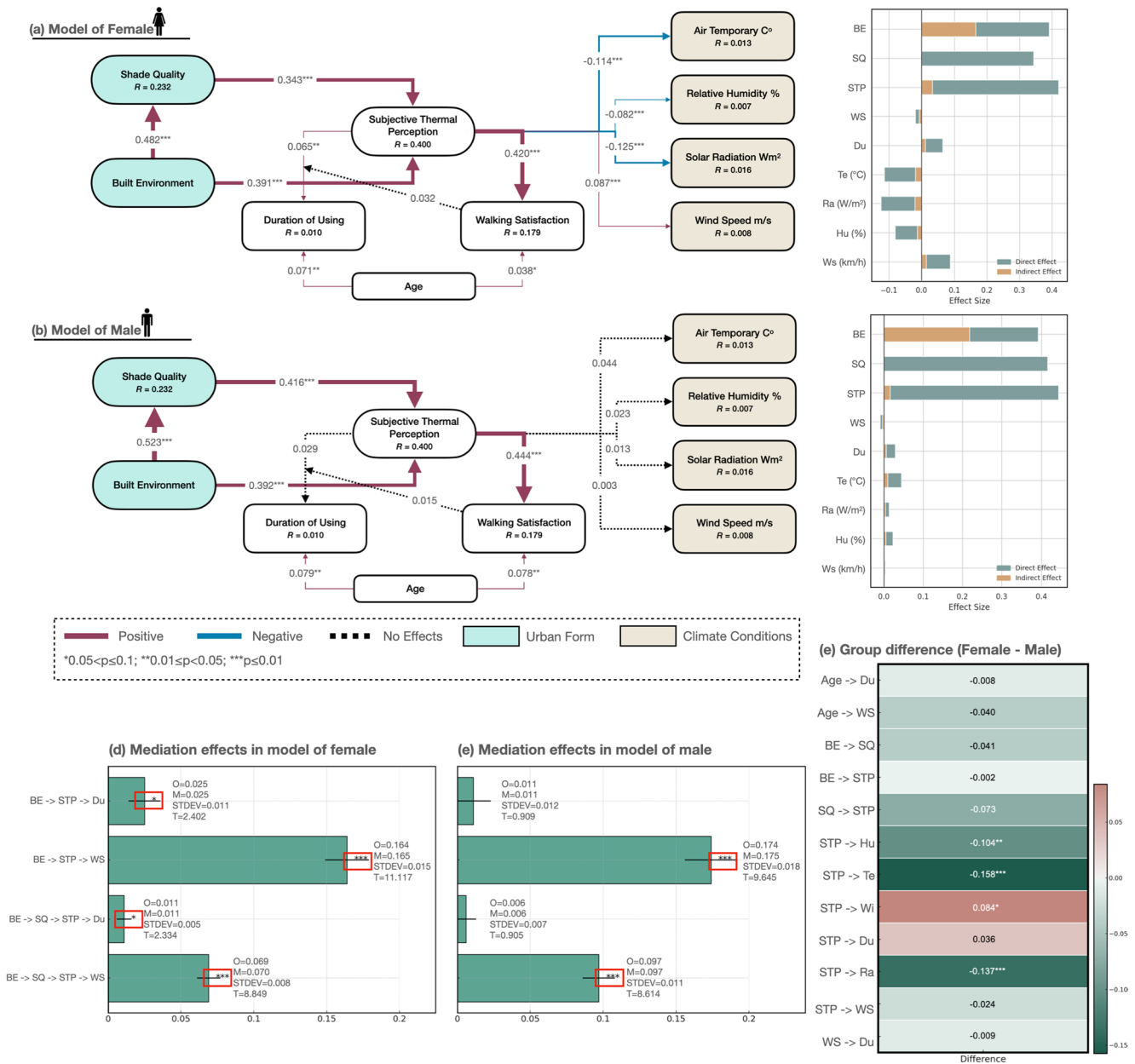
Climatic conditions during the investigation period (January–June 2023), derived from the Macao Meteorological and Geophysical Bureau, indicate progressive increases in heat exposure and solar load that frame pedestrian thermal experience in Macau's outdoor environments. To characterise typology-level shading performance and to support the scheduling of field surveys under peak exposure, a screening simulation was conducted in Ladybug (Rhinceros 8) using EPW climate input; the full modelling workflow, parameter settings, and output tables are reported in Supplementary Material A1. Figure 1 summarises the simulated shading outcomes across the four spatial typologies and demonstrates that shade availability within pedestrian walking

space varies systematically with morphological enclosure. Higher enclosure typologies (higher H/W) exhibit greater and more stable shade fractions, whereas more open typologies show lower shade fractions and stronger temporal sensitivity to solar position. Across seasonal screening dates, the lowest shade fractions occur around midday, indicating maximum sun exposure and minimal shading protection within the walking corridor. This evidence provides an objective basis for adopting the 11:00–13:00 fieldwork window, during which shading discontinuities are most likely to be experienced as thermal stress. Accordingly, Fig. 1 is used to (i) justify the standardised exposure window for survey administration and (ii) establish the typology context for interpreting shade quality perceptions, rather than to generate observed inputs for the SEM estimation.

## Structural equation modelling analysis

Validity and reliability test can be found in the supplementary material (Section A3 in SM). The structural results indicate a consistent perception-led pathway linking built-environment conditions, shade quality, subjective thermal perception, and walking outcomes (Fig. 2), with full coefficients, mediation effects, and multi-group tests reported in Supplementary Table C6, C7 and C8. The built environment significantly influences pedestrians' subjective thermal perception through its direct impacts on shading quality and environmental comfort. Specifically,  $BE \rightarrow SQ$  is significant for both males ( $\beta=0.523$ ,  $t=22.079$ ) and females ( $\beta=0.482$ ,  $t=21.807$ ), and  $SQ \rightarrow STP$  is significant for both males ( $\beta=0.416$ ,  $t=12.987$ ) and females ( $\beta=0.343$ ,  $t=12.670$ ) (Supplementary Table 4). In addition,  $BE \rightarrow STP$  remains statistically supported in both groups (males:  $\beta=0.122$ ,  $t=4.575$ ; females:  $\beta=0.155$ ,  $t=6.190$ ) (Supplementary Table 4). Subjective thermal perception is positively associated with walking satisfaction in both groups (males:  $\beta=0.444$ ,  $t=17.150$ ; females:  $\beta=0.420$ ,  $t=19.712$ ) (Supplementary Table 4). However, the direct  $STP \rightarrow DU$  association is not statistically supported for males but is supported for females (females:  $\beta=0.065$ ,  $t=2.421$ ) (Supplementary Table 4). Moreover, the moderation effect is not supported in either group ( $WS \times STP \rightarrow DU$ : males  $\beta=0.001$ ,  $t=0.038$ ; females  $\beta=0.012$ ,  $t=0.453$ ) (Supplementary Table 4).

Mediation results provide further evidence on how built-environment influences are transmitted through subjective thermal perception and shade quality. For walking satisfaction, indirect effects are supported in both groups: for males,  $BE \rightarrow STP \rightarrow WS$  is significant ( $B=0.174$ ,  $p<0.001$ ; bias-corrected CI [0.145, 0.205]) and  $BE \rightarrow SQ \rightarrow STP \rightarrow WS$  is significant ( $B=0.097$ ,  $p<0.001$ ; CI [0.079, 0.116]); for females,  $BE \rightarrow STP \rightarrow WS$  is significant ( $B=0.164$ ,  $p<0.001$ ; CI [0.141,



**Fig. 2** Model analysis results

0.190]) and  $BE \rightarrow SQ \rightarrow STP \rightarrow WS$  is significant ( $B=0.069$ ,  $p<0.001$ ;  $CI [0.057, 0.083]$ ) (Supplementary Table 5). In contrast, mediation toward duration of use is supported only among females ( $BE \rightarrow STP \rightarrow DU$ :  $B=0.025$ ,  $p=0.016$ ;  $CI [0.008, 0.043]$ ;  $BE \rightarrow SQ \rightarrow STP \rightarrow DU$ :  $B=0.011$ ,  $p=0.020$ ;  $CI [0.003, 0.019]$ ), whereas the corresponding indirect effects are not supported for males (Supplementary Table 5). Therefore, the model indicates a shared mechanism for walking satisfaction across gender groups, whereas duration-related mediation is evident only among females.

Gender differences in pathway magnitudes were evaluated using formal multi-group tests, rather than inferred from

coefficient comparison. No statistically supported between-group differences are identified for the core behavioural-path links ( $BE \rightarrow SQ$ :  $p=0.203$ ;  $BE \rightarrow STP$ :  $p=0.964$ ;  $SQ \rightarrow STP$ :  $p=0.082$ ;  $STP \rightarrow WS$ :  $p=0.472$ ;  $STP \rightarrow DU$ :  $p=0.379$ ) (Supplementary Table 6). Accordingly, the results indicate broadly comparable structural link strengths for the main perception-led pathway across gender groups. Nevertheless, significant between-group differences are observed in the associations between subjective thermal perception and concurrent objective microclimatic indicators ( $STP \rightarrow$  relative humidity:  $p=0.005$ ;  $STP \rightarrow$  air temperature:  $p<0.001$ ;  $STP \rightarrow$  wind speed:  $p=0.023$ ;  $STP \rightarrow$  solar radiation:  $p<0.001$ )

(Supplementary Table 6), indicating gender-related heterogeneity in the correspondence between perceived thermal state and objective conditions. Collectively, these results support a mechanism-based interpretation in which shade quality and subjective thermal perception function as key transmission stages for walking satisfaction in both groups, while duration-related mediation is supported only among females.

## Discussions

This research addresses significant theoretical gaps in urban walkable spaces in a hot city by systematically integrating subjective thermal perceptions into the analytical framework, thereby enhancing the theoretical understanding of pedestrian comfort within thermal climate-sensitive urban environments. Previous studies largely focused on physical attributes such as street configurations, shading provisions, and greenery impacts independently, with thoroughly limited exploring how these environmental elements interact with pedestrians' subjective perceptions and behaviors. This study explicitly bridges this theoretical void by adopting climate-informed PLS-SEM modeling, elucidating nuanced mechanisms through which urban form and shading quality influence subjective thermal comfort and pedestrian behavioural outcomes. Given the cross-sectional design, the estimated relationships are interpreted as associations consistent with the proposed pathway, rather than as causal effects.

### Subjective thermal perception as the core mechanism linking shading to walking experiences

A central contribution of this research is that the results indicate subjective thermal perception operates as a key mediating construct linking shade quality to walking outcomes, with mediation patterns differing by outcome. Consistent with earlier work that identifies thermal perception as a decisive determinant of outdoor comfort and use of space (Klemm et al. 2015; Lin and Matzarakis 2008b; Nikolopoulou and Lykoudis 2006), the present analysis demonstrates that shade quality affects walking satisfaction and duration of public space use mainly through its influence on perceived thermal conditions. The direct effects of shade quality on behavioural outcomes remain limited once subjective thermal perception is accounted for, indicating that changes in shading only become behaviourally meaningful when they are perceptually registered as thermal relief.

This mediation structure refines theoretical understandings of outdoor thermal comfort by emphasising perception-led rather than purely physically led pathways. Previous studies have shown that shading from buildings and vegetation reduces solar radiation and improves comfort (Nasrollahi et

al. 2021; Ou and Lin 2023; Turner et al. 2023), often treating physical cooling as the main explanatory mechanism. The present findings extend this work by showing that pedestrians' responses to shading are governed by how changes in radiation, wind, humidity, and temperature are integrated into subjective thermal perception (Schweiker et al. 2017; Yang et al. 2024). Shade quality therefore matters not only because it alters mean radiant temperature but because it reshapes perceived thermal conditions in ways that either enable or constrain satisfaction with walking.

Existing research has documented that favourable thermal conditions support higher walking satisfaction and longer duration of stay (Klemm et al. 2015; Shoval et al. 2017). The current analysis confirms these relationships but shows that subjective thermal perception exerts its influence predominantly through satisfaction before affecting duration of use. Accordingly, the estimated relationships should be interpreted as associations consistent with the proposed sequence, rather than as causal effects. This layered sequence, in which built form shapes shading, shading shapes perceived thermal comfort, and perceived comfort governs walking outcomes, indicates that behavioural adaptation to heat in compact, high-density settings such as Macau is mediated by psychological interpretation of environmental conditions rather than by exposure alone. In Macau's dense pedestrian environments, where short-distance walking frequently involves rapid transitions between sun-exposed and shaded segments, this perception-led mechanism provides a context-relevant explanation of why shade continuity becomes behaviourally consequential.

### Gender-specific perceptual mediation and behavioural adaptation pathways

The gender comparison evaluates whether the perception-led pathway differs between females and males, and the evidence indicates that the main behavioural-path coefficients do not differ statistically between groups under the multi-group tests, despite descriptive variation in estimates. While prior studies have recognised that thermal perception and emotional responses vary demographically (Jamei and Rajagopalan 2017; Knez and Thorsson 2008), most work has not modelled these differences as explicit mediation structures. The present study advances this literature by distinguishing between (i) pathways that are statistically comparable across groups and (ii) gender-sensitive patterns that arise in the perceptual correspondence between subjective thermal perception and concurrent microclimatic conditions, as summarised in Table 1. The multi-group analysis therefore assesses whether the specified perception-led mechanism operates similarly across female and male pedestrians under comparable exposure conditions. This grouping does not assume

**Table 1** Gender-specific findings in comparisons

**Gender-related patterns in perceptual mediation and perceptual-microclimate correspondence**



Aspect	Female	Male	Theoretical Advancement
<b>Strength of Perceptual Mediation</b>	Indirect effects toward walking satisfaction and duration are supported; duration-related indirect effects are supported only in the female group (Table 5).	Indirect effects toward walking satisfaction are supported; duration-related indirect effects are not supported (Table 5).	Identifies outcome-specific mediation patterns and clarifies that duration-related transmission is group-contingent.
<b>Perceptual correspondence with objective microclimatic indicators</b>	Stronger correspondence between subjective thermal perception and objective conditions, with significant between-group differences for air temperature, relative humidity, solar radiation, and wind speed (Table 6).	Weaker correspondence between subjective thermal perception and objective conditions for the same indicators (Table 6).	Refines perceptual-microclimate correspondence as a gender-sensitive component of thermal interpretation.
<b>Outcome-</b>	Lower variability,	Higher variability,	Advances

Table 1 (continued)



Aspect	Female	Male	Theoretical Advancement
<b>stage heterogeneity in duration-related responses</b>	indicating predictable and coherent adaptive responses to shading interventions.	reflecting more individualized and less predictable adaptation strategies.	behavioural adaptation theory by attributing variability in thermal responses to differences in perceptual alignment and mediation strength.

homogeneity within either group; instead, it provides a parsimonious comparison of group-level patterning in subjective thermal perception, walking satisfaction, and duration of use. In the context of Macau, where everyday walking frequently occurs under hot-humid exposure and variable shade continuity, the gender comparison is used to clarify whether the translation from shade quality to perceived thermal conditions and walking-related outcomes is comparable across these two broad pedestrian groups. This contextual framing is particularly relevant in Macau because intensive pedestrian activity in compact urban settings increases the

practical salience of small differences in perceived thermal relief for routine route choice and outdoor engagement.

Females demonstrate a strong and coherent mediation chain from shade quality to subjective thermal perception and onwards to walking satisfaction and duration of use. As illustrated in Table 1, increases in shade quality are closely aligned with improvements in perceived thermal comfort, which in turn are consistently associated with higher walking satisfaction and indirectly with longer time spent in public spaces. This pattern indicates a high degree of perceptual alignment between environmental shading conditions and

thermal interpretation, and the mediation results indicate that duration-related indirect effects are supported among females. In theoretical terms, this pathway extends earlier propositions on heightened female sensitivity to thermal conditions (Knez and Thorsson 2008; Lin et al. 2013) by specifying a structured transmission in which shade-related improvements are more consistently translated into evaluative and duration outcomes through subjective thermal perception.

In contrast, males exhibit a more outcome-specific mediation structure rather than uniformly weaker effects. Shade quality still shapes subjective thermal perception, and subjective thermal perception remains positively associated with walking satisfaction; however, duration-related indirect effects are not statistically supported among males, indicating that extended stay is less consistently transmitted through the perception-led chain. Table 1 therefore indicates that behavioural responses among male pedestrians are less tightly organised around shade-dependent perceptual relief when the outcome is duration, which is consistent with prior arguments that demographic groups can employ different adaptive behaviours under similar thermal conditions (Chen and Ng 2012; Jamei and Rajagopalan 2017). Accordingly, the evidence supports heterogeneity primarily in the outcome stage and in perceptual correspondence, rather than in statistically distinct behavioural-path coefficients.

Gender-specific differences in mediation strength, perceptual alignment with shading quality, and behavioural variability (Table 1). Females exhibit stronger perceptual mediation, higher alignment between objective shading conditions and subjective assessment, and lower variability in adaptive responses. Males exhibit weaker mediation, lower alignment between shading conditions and perceived comfort, and greater variability in behavioural adaptation. To avoid overstatement, these contrasts are interpreted as patterns derived from the mediation results and from the significant gender differences in the associations between subjective thermal perception and objective microclimatic indicators, rather than as evidence of statistically different core behavioural-path coefficients. These distinctions refine thermal comfort theory by clarifying where gender-sensitive heterogeneity is empirically supported within a perception-led framework and where relationships remain statistically comparable across groups.

### Implications for heat-responsive and gender-aware shading design

The gender comparison informs urban design translation by indicating that shade quality is behaviourally relevant primarily through subjective thermal perception and that duration-related responses are more contingent across groups; therefore, operationalisation should prioritise perceptual relief while providing options for heterogeneous regulation. The differentiated mediation pathways have direct implications for the design and

planning of shading interventions in heat-exposed urban environments. The perception-led results support translating shading interventions into practice through mechanisms that improve subjective thermal perception and walking satisfaction, rather than through direct behavioural effects alone. Moreover, the multi-group evidence indicates that the main behavioural-path coefficients are statistically comparable across female and male groups; therefore, design implications are framed as inclusive, mechanism-based strategies that accommodate heterogeneous regulation rather than as prescriptive gender-divergent standards. Accordingly, shading practice should prioritise interventions that reliably improve perceived thermal conditions, while ensuring that diverse regulation strategies can be supported within the same public-space system. In Macau, where pedestrian movement concentrates along short, highly utilised street segments and activity nodes, this translation implies prioritising shade continuity and shade availability at high-exposure route connectors and waiting/lingering points.

For women, the mediation chain indicates higher reliance on shading cues for thermal interpretation and walking-related outcomes. Accordingly, a concrete strategy is to treat shade continuity as a “mobility infrastructure” along primary pedestrian desire lines, by reducing exposure gaps at crossings and intersections and by strengthening continuous canopy coverage on segments with high pedestrian throughput. Continuous and predictable shade along walking routes should therefore be prioritised. Closely spaced building masses, canopy trees positioned along pedestrian lines, and integrated shading structures that reduce exposure gaps can provide stable perceived relief from solar radiation. This approach supports shaded mobility corridors, linked canopy continuity, and consistent shade quality around key activity nodes where walking demand concentrates. However, these measures are positioned as baseline comfort-support for all pedestrians, while the gender comparison motivates additional attention to providing choice in how thermal relief is accessed and used.

While for men, the mediation structure suggests more variable behavioural translation from shading-related perception. Accordingly, operationalisation should extend beyond shade provision alone by pairing shade with complementary microclimatic choices that support alternative regulation strategies, including ventilation-supportive alignments, shaded resting pockets, and short-distance shaded–sun transitions that enable self-selection. Heat adaptation in these contexts may benefit from shade combined with airflow corridors, evaporative features, and short distance sunshade variation that enables selection among microclimatic options.

Inclusive design can therefore be achieved through an “option-set” approach rather than a prescriptive gender split: maintain a baseline standard of continuous shade on key routes and high-use nodes, while embedding adjacent microclimatic alternatives (shade + airflow, shade + seating, shaded–sun

sequences) within short walking distance. The findings support a zoning logic in which some routes and plazas prioritise continuous shade for shade dependent users, while others incorporate mixed microclimate conditions to accommodate diverse regulation strategies. Overall, the results extend climate-responsive and inclusive design debates by grounding shading strategies in observed perceptual behavioural pathways rather than aggregate comfort indices alone, indicating that shading should be allocated in relation to both climatic burden and perceptual alignment with shade quality.

## Limitations

Given Macau's geographic location and visitor demographics, the majority of participants in this study were from East and Southeast Asia. As a result, the findings predominantly reflect perceptual and behavioural tendencies of populations within this cultural region, and transferability to other continents should be tested through replication. Secondly, the analysis focused on gender as a key grouping variable, while age was included as a parsimonious control. Although this approach supports a mechanism-focused comparison, other factors—such as cultural background or thermal adaptation history—may also influence subjective thermal responses and can be incorporated in future studies where broader behavioural-context explanation is required. Third, the study was conducted in a single case city characterised by a compact urban form, subtropical climate, and specific socio-spatial conditions; therefore, applicability to cities with different morphological, climatic, or cultural contexts requires further validation. Moreover, because key constructs were collected using the same survey instrument at a single time point, common-method bias cannot be fully excluded; however, the measurement model was evaluated using established reliability and validity diagnostics. In addition, responses collected between January and June were analysed jointly to represent a documented range of thermal conditions in Macau rather than a single-season snapshot; seasonal stratification can be considered in future work designed for seasonal comparison. Finally, the intercept survey design may constrain representativeness because participation depends on availability and willingness at specific locations and times; therefore, the results should be interpreted as mechanism evidence for the sampled pedestrian population rather than as population prevalence estimates.

## Conclusions

This study advances the theoretical and empirical understanding of walkability by establishing a perception-led pathway through which thermal comfort shapes walking outcomes in high-density urban environments under climatic stress.

Existing research has largely treated thermal comfort as either an environmental condition or a uniform human response. This study departs from that framing by showing that subjective thermal perception is a key determinant of walking satisfaction and functions as the principal mechanism translating perceived shade quality into walking-related evaluation and, more conditionally, duration of public-space use.

By integrating climatic data, environmental simulation, and PLS-SEM modelling, the research demonstrates a structured sequence in which urban built form shapes shade quality, which influences subjective thermal perception, which in turn is associated with walking satisfaction and indirectly with duration. The multi-group evidence indicates that the core behavioural-path coefficients are statistically comparable across female and male groups; however, gender-sensitive heterogeneity is evident in the perceptual linkage between shade quality and subjective thermal perception and, more clearly, in the associations between subjective thermal perception and concurrent microclimatic indicators, as well as in duration-related indirect effects.

These findings indicate that environmental enhancements such as shading should be interpreted through how pedestrians register thermal relief, rather than through physical shade provision alone. Therefore, climate-resilient planning should prioritise shade continuity and perceptual thermal relief along high-use routes and activity nodes, while providing microclimatic options that support heterogeneous regulation under hot-humid exposure. Future studies should test transferability across cities and demographic profiles and examine additional behavioural-context factors where the objective extends beyond mechanism estimation.

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**Data availability** The datasets presented in this study can be found in online repositories: DOI: <https://doi.org/10.17605/OSF.IO/MEV8S>; URL: <https://osf.io/mev8s/>.

## Declarations

**Ethics approval** Macau University of Science and Technology Medical Ethics Committee approved the study (Approval Number: MUST-20240430001).

**Consent for publication** Not Applicable.

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Human Ethics and Consent to Participate** The study was conducted in accordance with the Declaration of Helsinki, all questions in investigation questionnaire were reviewed and approved by the Institutional Review Board (or Ethics Committee) of MACAU UNIVERSITY OF SCIENCE AND TECHNOLOGY (protocol code: MUST-20240430001 date of approval: 05-10-2022). Informed consent to participants were provided at the beginning of the questionnaire for each participant, which clearly state the use of information and privacy protection policies for agreement.

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