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Multilevel structural equation modelling of walkability in a motorcycle-dominated city: A case study of Da Nang, Vietnam

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ABSTRACT

In Southeast Asian cities, rapid urbanisation, characterised by a motorcycle-dominated landscape, has eroded pedestrian infrastructure and compromised walkability. Conventional frameworks, primarily rooted in temperate, car-centric contexts, inadequately capture micro-scale, climate-sensitive, and encroachment-specific conditions. The lack of models that integrate objective audits with subjective perceptions further limits their relevance to context-specific, evidence-based interventions. Focusing on Da Nang, Vietnam, this study proposes and validates a Multilevel Structural Equation Modelling framework that coherently links objective built-environment audits with subjective pedestrian perceptions, grounded in Alfonzo's Walking Needs Hierarchy. Using a mixed-methods design, 720 on-site surveys and structured field audits are conducted across 30 urban locations.

At the individual level, Accessibility has the most substantial effect on perceived environmental quality, followed by Comfort, Safety, and Pleasurability, which together account for 51.7% of the variance. Accessibility shows the largest standardised effect, with comfort more prominent than its theoretical position implies, reflecting a context-specific emphasis. At the location level, objective environmental quality is strongly associated with perceived environmental quality, accounting for 71.1% of the between-location variance. Additional spatial analysis reveals significant inequalities, with land use for tourism and recreation prioritised over areas that provide essential services. The study contributes a methodological operationalisation of MSEM integrating subjective and objective walkability indicators at their respective analytical levels; the empirical multilevel test of the Walking Needs Hierarchy in a tropical, motorcycle-dependent setting; and new evidence on micro-scale stressors in a Global-South urban context. The findings provide evidence-based insights to inform pedestrian-oriented planning in rapidly urbanising regions of the Global South.

1. Introduction

Southeast Asia is undergoing rapid urbanisation, characterised by high-density, mixed-use urban forms that have developed organically rather than through formal planning. A key feature of this transformation is the dominance of motorcycles, which serve as the primary mode of transport in many cities (Van Nguyen & Truong, 2025). While this shift enhanced individual mobility and regional connectivity, it also reshaped urban spaces, marginalising non-motorised transport. This created a unique urban fabric in which public space is continuously negotiated among pedestrians, a massive fleet of motorised two-wheelers, and informal economic activities. Walkability, which has long been associated with vibrant, inclusive, and healthy urban environments, is increasingly being sidelined in spatial planning (Sallis et al., 2016).

The lack of attention given to pedestrian infrastructure directly influences the quality of urban spaces and public health conditions. Where sidewalks have been established, they are often overrun by motorcycles and vendors, fragmenting pedestrian facilities and forcing pedestrians into conflict with traffic (Leung & Le, 2019). Streets are typically designed for traffic flow rather than human needs. In addition, environmental stressors such as high heat inherent to hot-humid climates and the noise associated with high motorcycle traffic levels contribute to sensory overload and physical discomfort (Mouratidis, 2021). These barriers discourage walking as a viable mode of transport, reduce physical activity, and exacerbate spatial exclusion, particularly for vulnerable populations (Van Nguyen & Truong, 2025).

Such challenges underscore the need for an in-depth analysis of walkability in the given context. Walkability has gained recognition

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as a cornerstone of sustainable urban development, with contemporary research emphasising its multidimensional nature, requiring both an objective assessment of the built environment and a subjective assessment of the pedestrian experience (Frank et al., 2006). However, existing measures inadequately represent essential dimensions of pedestrian experience within tropical, motorcycle-dominated cities in the following three aspects: (*i*) the methodological disconnect between objective built-environment data and subjective pedestrian perceptions; (*ii*) the absence of context-specific stressors, such as thermal comfort and motorcycle encroachment; and (*iii*) the lack of validation for theoretical walking needs hierarchy to ensure truly human-centred planning for such unique, informal urban settings. These methodological and contextual gaps limit both the explanatory power of walkability models and their relevance to policy. Consequently, context-inappropriate interventions are likely to contribute to congested, traffic-dominated streetscapes, hindering pedestrian activity and undermining the aims of sustainable transport and public health.

To bridge these gaps, this study proposes a multilevel structural equation modelling (MSEM) framework that systematically integrates objective location audits and subjective individual perceptions based on the Walking Needs Hierarchy (Alfonzo, 2005). The assessment scale is adapted to the context to reflect the challenges faced by motorcycle-dependent tropical cities, including sidewalk encroachment, thermal discomfort, and motorcycle traffic. The study focuses on the context of Da Nang, Vietnam, a rapidly urbanising coastal city positioning itself as a smart city and liveable tourism destination, serving as a representative case. A mixed-methods approach is employed, combining field audits and pedestrian surveys with 720 respondents across 30 locations.

Building on this design, the study makes three complementary contributions. First, methodologically, it operationalises MSEM to simultaneously estimate subjective walkability dimensions at the within-individual level and audit-derived environmental attributes at the between-location level within a single hierarchical model. Although SEM has been increasingly applied to transport behaviours in the Global South, including biogas-fuelled bus rapid transit adoption in Karachi (Baig et al., 2024) and ride-hailing discontinuance in Lahore (Basheer et al., 2025), multilevel extensions remain scarce. Existing MSEM applications, such as Guo et al. (2021) on built-environment correlates of mental wellbeing among older adults in Hong Kong, and Wisutwattanasak et al. (2025) on e-bicycle sharing intentions among older residents in regional Thailand, address outcomes other than walking experience and do not anchor their multilevel structure in a pedestrian-needs framework. To our knowledge, the present study constitutes the first walkability-specific MSEM application to jointly model these dual channels at the within-individual and between-location levels, respectively, with the structural specification grounded in Alfonzo's Walking Needs Hierarchy (Alfonzo, 2005). This dual-channel design mitigates the ecological and atomistic fallacies inherent in single-level approaches (Diez Roux, 2002). Second, theoretically, the study provides an empirical multilevel test of Alfonzo's Walking Needs Hierarchy in a tropical, motorcycle-dominated setting, examining the extent to which the originally proposed ordering is reflected in the relative magnitudes of the within-level effects under local conditions. Third, empirically, it generates fine-grained evidence on micro-scale stressors (sidewalk encroachment, motorcycle noise, and thermal load) that remain under-represented in walkability research beyond Western urban settings (Ahsan et al., 2023).

2. Literature review

2.1. Conceptualising urban walkability: Objective and subjective dimensions

The concept of walkability has undergone significant changes, expanding far beyond a narrow emphasis on infrastructure aspects to a broader understanding of how cities effectively enable and encourage walking for a variety of purposes (Frank et al., 2006). Walkability integrates both the physical elements of the urban environment (e.g., sidewalk connectivity, land-use diversity) and the perceptual aspects (e.g., security, aesthetic appeal) (Saelens & Handy, 2008; Saadi et al., 2022). As a multidimensional concept, walkability is integral to sustainable cities (Asadi-Shekari et al., 2015). Contemporary studies investigate walkability through both objective measures based on physical environmental features and subjective measures that capture pedestrian perceptions (Saadi et al., 2022). Objective data provide standardised, replicable insights into the built environment, whereas subjective data reflect how individuals perceive, interpret, and react to the surroundings. Integrating both types of data provides comprehensive insights into how urban environments shape walking behaviour (Huang et al., 2024).

Despite growing recognition of the dual importance of both dimensions, current studies remain limited in scope and methodological approaches (Huang et al., 2024). Current integration methods fall into two categories. The first approach is a parallel analysis, in which both types of data are collected but analysed separately, either in distinct statistical models or through a simple comparison of outcomes (Gao et al., 2022). The second approach incorporates them into a single model, but only after forcing the data onto the same analytical level: either by assigning objective area-level data to individuals (e.g., Nyunt et al. (2015)), or by aggregating individual subjective perceptions into average scores representing the area (e.g., Zeng et al. (2022)). These may result in biased or incomplete deductions concerning the real relationship between the subjective experience and the objective environment. Adding to this problem is the challenge of spatial inequality, particularly in developing cities. This difference, stemming from variations in policy design and physical characteristics between locations (Pojani & Stead, 2015), creates significant heterogeneity in the walking environment. The single-level models, such as regression analysis and structural equation modelling, are insensitive to this disparity at the neighbourhood level (Wisutwattanasak et al., 2025).

Such limitations point to an existing methodological gap in the literature: the lack of a hierarchical model that treats subjective and objective data at their respective levels to model their interactions. To address this shortcoming, this study proposes an MSEM analytical framework that systematically integrates both data sources to consider walkability in complex urban environments.

2.2. Micro-scale assessment and challenges in hot-humid, motorcycle-dominated urban environments

Walkability assessments generally fall into two categories: macro-scale and micro-scale. Macro-scale models are spatial frameworks used to quantify walkability across large geographical areas (Frank et al., 2006). Commonly conducted using geographic information systems, they assess broad urban patterns, for instance, land-use mix and network density (Saelens & Handy, 2008). Notable examples include Ewing and Cervero's "5Ds" (density, diversity, design, destination accessibility, and distance to transit) framework (Ewing & Cervero, 2010) and Walk Score (Carr et al., 2010), which are widely applied in transportation and public health research. Despite their scalability and systematisation, they rely on aggregated spatial data that neglects localised barriers and walking experience (Southworth, 2005). To address these challenges, micro-scale audit tools have been developed to systematically evaluate street-level features that directly influence pedestrian experience (Clifton et al., 2007). Key aspects are sidewalk presence and quality (width, surface condition), streetscape elements (trees, lighting), the traffic environment (crosswalks, traffic calming), and safety or accessibility features (curb cuts, ramps) (Saelens & Handy, 2008; Asadi-Shekari et al., 2015). Early attempts, such as the Pedestrian Environment Audit Tool (PEAT) (Troped et al., 2006) and the Walking Suitability Assessment Form (WSAF) (Emery et al., 2003), focused on objective aspects such as the sidewalk width and traffic flow. More extensive audits, including the Pedestrian Environmental Data Scan (PEDS) (Clifton et al., 2007) and PIN3 Instrument (Evenson et al., 2009), examined both infrastructure and qualitative elements such as maintenance. In contrast, the Neighbourhood Environment Walkability Scale (NEWS) (Saelens et al., 2003) measures subjective perceptions such as safety, aesthetics, and accessibility.

In low- and middle-income countries, the preference for micro-scale urban research is on the rise, as it provides cost-effective, practical solutions and is more viable given the limited availability of fine-grained spatial data (Koohsari et al., 2021). Recent Global-South evidence further confirms the salience of micro-scale stressors: in Lahore, Ahsan et al. (2023) document that sidewalk discontinuity, motorised encroachment, and thermal exposure are the dominant perceived barriers to walking; comparable patterns are reported in Bangkok (Ratanawichit et al., 2025). Moreover, the urban typologies found in such settings are usually high-density and mixed-use, often the result of unmanaged growth rather than formal planning (Chen et al., 2020), thereby affirming the need to consider micro-scales in the analysis process. Accordingly, this study adopts a micro-scale, context-sensitive lens to assess walkability in Vietnam. However, despite their localised focus, existing micro-scale tools often reflect assumptions rooted in Western planning paradigms. They inadequately account for the spatial, cultural, and climatic realities of tropical cities, particularly those dominated by motorcycles (Pojani & Stead, 2015). This raises the need not only to apply but also to adapt and examine in these unique urban settings.

In many Southeast Asian cities, walkability is shaped less by formal infrastructure than by the negotiation of informal management of public spaces by pedestrians themselves (Kamalipour & Peimani, 2019). Motorcycles, parking, and informal vending are often found blocking sidewalks, narrowing pathways and disrupting pedestrian facilities (Leung & Le, 2019). These intrusions fragment the pedestrian network and restrict equitable access to public spaces. Also, the lack of a distinct separation between pedestrian and vehicle zones increases the likelihood of conflict, as motorcycles often encroach on the walking area during peak times (Gota et al., 2010; Ho et al., 2023). These spatial problems are intensified by environmental stressors. In a hot-humid climate, high thermal loads induce fatigue and avoidance behaviour, even in well-designed spaces (Wang et al., 2022), whereas noise, pollution, and irregular traffic chaos cause psychological stress (Mouratidis, 2021). Interestingly, informal uses of sidewalks enliven the street scene, encouraging urban vitality, interaction, and cultural identity (Dovey & Recio, 2024). Such contradictory conditions, where vitality coexists alongside conflict and discomfort, are at the heart of the pedestrian experience in such spaces.

These dynamics underscore that walkability in tropical, motorcycle-oriented cities is context-specific and cannot be meaningfully assessed using standardised indices alone. Emerging scholarship calls for a reconceptualisation of walkability as a place-based practice shaped by local spatial and social conditions (Schiller & Kenworthy, 2017). This study responds to that need by adapting micro-scale assessments to street-level walkability in the Global South.

2.3. Subjective individual-level predictors: The hierarchy of walking needs

2.3.1. The human-centric approach

To effectively understand walkability perception at the individual level, it is imperative to adopt a human-centric approach. This paradigm marks a decisive shift away from traditional planning metrics, which often prioritise traffic flow and infrastructure efficiency, towards a focus on the social and human dimensions of mobility (Pawlyszyn & Ryzhkova, 2021). This frames mobility planning within community values, individual needs, and well-being (Mouratidis, 2021), leading to greater public engagement than conventional approaches. To better align with human-centric paradigms for urban mobility, qualitative models such as the 5C model (Gardner et al., 1996) and the General Theory of Walkability (Speck, 2012) provide important frameworks

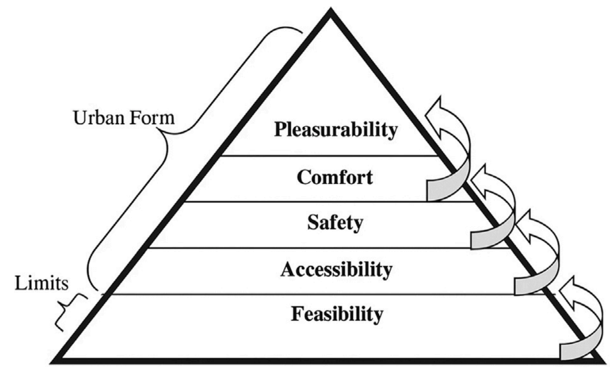

Fig. 1. The Walking needs hierarchy (Alfonzo, 2005).

for designing environments that prioritise pedestrian needs and well-being. The 5C model highlights comfort, connection, conspicuousness, convenience, and conviviality, thus creating a holistic approach to meeting pedestrian needs. Similarly, the four pillars of the General Theory of Walkability focus on ensuring safety and usefulness while fostering an engaging and comfortable environment for pedestrians. However, these models fall short of providing a clear hierarchy of pedestrian needs. Meanwhile, Alfonzo's Hierarchy of Walking Needs (WNH) (Alfonzo, 2005) offers a structured framework that prioritises key factors influencing pedestrian decision-making, aligning urban mobility planning with pedestrian needs.

As illustrated in Fig. 1, the WNH conceptualises walking as a sequential, need-based behaviour across five interdependent levels. In which walkability attributes are organised into four urban form factors: Accessibility, Safety, Comfort, and Pleasurability. Meanwhile, Feasibility, an individual indicator of whether someone can walk, is typically used as a control variable rather than a standalone construct (Sapawi & Said, 2018). The WNH thus provides a theoretically grounded, context-sensitive approach to assessing walkability that expresses both fundamental and experiential needs. This serves as a practical roadmap for urban designers and policymakers, guiding pedestrian improvements through sequential, evidence-based steps (Distefano et al., 2023). As a preliminary step in this unique study context, this study adopts the WNH with four urban form dimensions.

2.3.2. The Walking Needs Hierarchy dimensions

Accessibility: Accessibility refers to the ease with which pedestrians can reach essential services, factoring in proximity to services, and the absence of physical barriers (Southworth, 2005). In Southeast Asian cities, sidewalk obstructions, including informal motorcycle parking and street vendors, reduce accessibility and hinder smooth pedestrian flow. The fragmentation of pedestrian networks exacerbates this issue, making it more difficult for people to travel freely on foot (Leung & Le, 2019).

Existing measurement tools often overlook the importance of these informal urban practices when evaluating walkability. As suggested by the WNH (Alfonzo, 2005), accessibility is the most fundamental dimension of walkability among urban form factors. The foundational, unobstructed pedestrian access must be satisfied before higher-order needs. Emerging evidence suggests that improved accessibility enhances both the functional and perceived quality of the walking environment (Yu et al., 2024). In Da Nang, the convenience of motorcycles for short trips has reinforced their dominance in daily travel. This widespread use contributes to frequent sidewalk obstructions from parked motorcycles, vendors, and informal structures, making walking increasingly impractical. These barriers limit pedestrian mobility and shape residents' perception of the urban environment. In such a context, improving accessibility is expected to enhance the perceived quality of the walking environment. The first hypothesis is thus developed as follows:

H1: Accessibility has a positive effect on perceived environmental quality

Safety: Safety represents the next level in the WNH (Alfonzo, 2005), encompassing both perceived protection from traffic and social threats (Saelens et al., 2003). Safety concerns regarding traffic interactions, harassment, and crime can impede walking activities and negatively affect urban environments (Loukaitou-Sideris, 2006). Safety in Southeast Asia is influenced by infrastructure quality, traffic safety, and environmental factors, with inadequate infrastructure exacerbating vulnerabilities (Gota et al., 2010).

In urban Vietnam, in addition to the lack of clear separation from motorised traffic (Ho et al., 2023), also a traffic culture that increases risks for pedestrians. Motorcycles often fail to yield at intersections without traffic lights, even with crosswalks present. Pedestrians frequently cross at their convenience, and drivers do not consistently follow posted speed limits. This impacts perceived safety, even with adequate infrastructure in place. Research in Da Nang has also identified traffic safety as an important factor contributing to the development of walkable urban areas (Nguyen-Phuoc et al., 2018). Once basic accessibility is ensured, safety becomes the next essential need influencing pedestrian behaviour (Alfonzo, 2005). Evidence suggests that when pedestrians feel safe, they are more likely to find their walking environment comfortable, attractive, and usable (Southworth, 2005). Hence, the following hypothesis is proposed:

H2: Safety has a positive effect on perceived environmental quality

Comfort: Comfort represents a transitional level in the WNH framework, becoming salient after accessibility and safety needs are met. Comfort is the sense of ease arising from reduced traffic stress, high-quality sidewalks, weather protection, and ample amenities (Alfonzo, 2005). Walkability studies in Southeast Asian tropical cities emphasise the role of both urban design and climate in pedestrian comfort (Wang et al., 2022). Thermal stress, along with other discomfort factors such as poor sidewalk quality and noise pollution, has been shown to significantly affect pedestrian satisfaction (Wang et al., 2022). Despite the development of various walkability tools, few integrate thermal comfort into evaluations of pedestrian comfort (Labdaoui et al., 2021).

In Vietnam, motor vehicle-oriented urban design often results in inconsistent or poor pedestrian comfort, especially in hot, humid cities like Da Nang. In such climates, comfort should be carefully addressed to ensure walking is both feasible and appealing (Nguyen-Phuoc et al., 2018). Once accessibility and safety needs are met, comfort becomes essential, enhancing walking satisfaction, reducing fatigue, and improving the walking environment quality (Alfonzo, 2005). Accordingly, the following hypothesis is proposed:

H3: Comfort has a positive effect on perceived environmental quality

Pleasurability: As the highest-order need in the WNH, pleasurability emerges only after basic needs are met. It refers to the sensory, aesthetic, and emotional gratification derived from walking, which is influenced by features such as greenery, architectural variety, vibrant street life, and visual stimuli (Southworth, 2005). Unlike utilitarian walking, pleasurable environments invite exploration, lingering, and positive affect. Studies have linked pleasurability to increased walking frequency, satisfaction, and perceived environmental quality (Lindelow et al., 2014).

Moreover, pleasurability should be evaluated based on factors that are appropriate to the local context (Uysal Üner & Cubukcu, 2025). For example, with Vietnam's collectivist culture, social spaces are of significant importance. As a coastal city, Da Nang benefits from riverfront promenades and beachside paths, making pleasurability a vital factor in determining walkability for residents and visitors. Within the WNH framework (Alfonzo, 2005), pleasurability, while not as urgent as other needs, remains significant and influences the perceived quality of the walking environment. Therefore, the hypothesis is proposed as follows:

H4: Pleasurability has a positive effect on perceived environmental quality

2.4. Objective location-level predictor: Objective environmental quality

The theoretical proposition that the physical environment shapes human perception is a cornerstone of environmental psychology. Foundational theories posit that the objective, physical attributes of a setting provide the essential stimuli that underlie subjective evaluation (Kaplan & Kaplan, 1989). This view is complemented by the concept of "behaviour settings" (Barker, 1968), which argues that specific configurations of environmental features elicit predictable patterns of perception and social interaction. Within this framework, the street-level built environment constitutes a "setting" whose measurable qualities structure the potential for human experience. Objective environmental quality (OEQ), defined in the study as a latent construct of the location environment, is theoretically conceptualised as reflecting a single underlying property of the street setting. Heterogeneous streetscape attributes (sidewalk availability and width, crosswalk quality, number of lanes, lighting, trees, etc.) are treated as joint indicators of this latent quality because they share a common antecedent: the level of integrated design and management investment directed towards pedestrian use.

Two complementary theoretical mechanisms underpin this conceptualisation: behaviour-settings theory treats the street segment as a bounded socio-physical unit in which milieu and behaviour are mutually constitutive (Barker, 1968), while ecological-affordance theory holds that configurational properties of physical settings afford behavioural patterns through their joint arrangement (Gibson, 2014). The complete-streets literature (McCann, 2013) documents that walkable streets are produced by integrated design decisions that bundle multiple supportive features, and assessment frameworks for the walking environment identify multiple interrelated domains as joint elements of a single construct (Pikora et al., 2003). Empirical precedents in walkability research support this approach: walkability indices that aggregate multi-attribute components have been validated for walking-behaviour research (Frank et al., 2010), principal-components analyses of multi-attribute walkability composites have extracted a single dominant component with acceptable internal consistency (Mayne et al., 2013), and micro-scale audit summary scores aggregating heterogeneous features show the strongest associations with walking, reflecting the cumulative impact of numerous environmental attributes (Cain et al., 2014). The reflective single-factor specification adopted here is therefore grounded in this convergent theoretical tradition (Ewing & Handy, 2009) and is consistent with prior empirical evidence on walkability composites.

Empirically, variations in objective design attributes are systematically related to residents' perceptions of walkability (Gebel et al., 2011). Because perception is jointly shaped by environmental affordances and individual-level filtering processes such as attention, prior experience, and contextual sensitivity (De Vos et al., 2023; Gibson, 2014), this link is best conceptualised as a systematic statistical association mediated by individual and contextual variation rather than a deterministic causal mapping. Accordingly, H5 is formulated and tested as a positive association between objective and perceived environmental quality under the present cross-sectional design.

H5: Objective environmental quality is positively associated with perceived environmental quality

2.5. The conceptual model

Building upon the identified hypotheses and arguments, this study proposes a conceptual model to empirically test the determinants of perceived environmental quality. Perceived environmental quality refers to the degree to which urban settings promote and facilitate walking, encompassing both physical attributes and pedestrian perceptions (Baobeid et al., 2021; Zumelzu et al., 2022). This model advocates for a hierarchical framework that integrates objective and subjective dimensions of walkability at their respective analytical levels, offering a more comprehensive understanding of urban walkability.

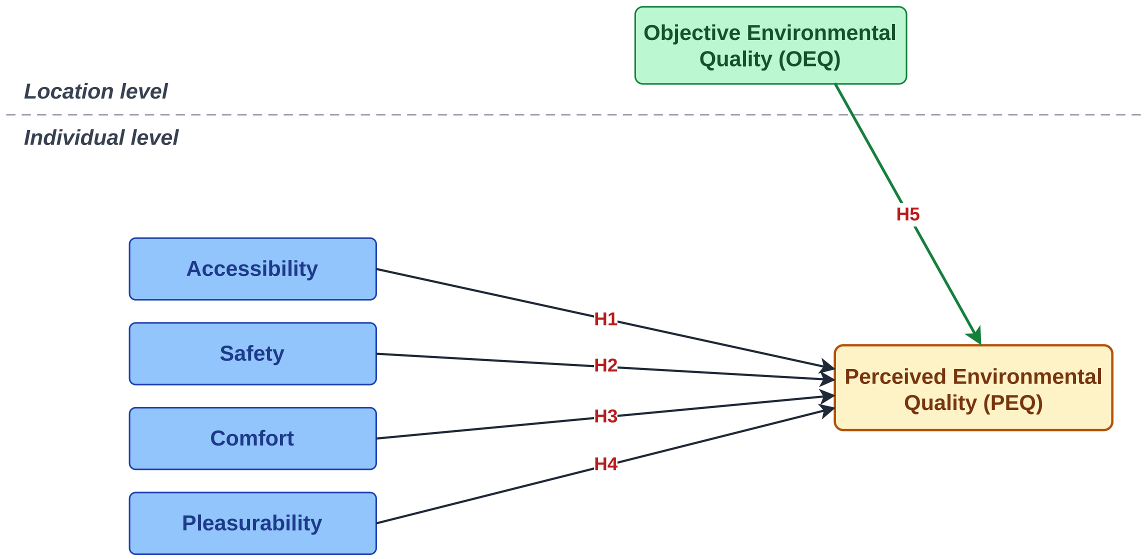

Fig. 2. The conceptual model.

As illustrated in Fig. 2, the model operates across two levels. The individual level incorporates subjective factors drawn from the WNH, which posits that four core needs function sequentially to shape pedestrian perceptions: Accessibility, Safety, Comfort, and Pleasurability. At the location level, the model captures objective environmental quality, which represents the objective, physical aspects of the urban environment that influence pedestrian experiences. This framework enables the empirical testing of the direction and significance of each within-level walking need alongside the objective contributions of the built environment.

Overall, the literature review confirms that contemporary walkability demands a dual-lens approach that acknowledges both objective built environment features and subjective pedestrian perceptions. The review, however, underscores the critical gaps. First, there is a methodological disconnect: studies frequently analyse built environment data and pedestrian perceptions separately, lacking an integrated framework that accounts for their interaction across spatial dimensions. Second, studies often overlook locally salient stressors, such as thermal discomfort and encroachments, which significantly shape pedestrian experience in tropical and informally structured cities. Third, while hierarchical models of pedestrian needs have been conceptually proposed, their empirical grounding remains weak. To address this, this study proposes an MSEM framework. This model is underpinned by the WNH at the individual level and objective environmental quality at the location level, enabling an empirical test of the direction and significance of each within-level need alongside contextual effects. The indicators are carefully tailored to local challenges, such as sidewalk encroachment, the pervasive impact of motorbike traffic, and exposure to thermal stress. In doing so, it advances a context-sensitive and empirically validated model that informs more inclusive, human-centred urban design approaches for cities in the Global South.

3. Methodology

3.1. Scale development

At the individual level, the measurement scale comprises 21 indicators, categorised into four dimensions: Accessibility, Safety, Comfort, and Pleasurability. This is assessed through an on-site questionnaire survey in which pedestrians rate their experience using a five-point Likert scale. The indicators are drawn from a synthesis of theoretical frameworks, empirical studies, and adaptations to the local context of Da Nang, Vietnam, where the urban core is densely populated, motorcycles are prevalent, and the climate is tropical. The Accessibility dimension comprises six indicators that address service accessibility and obstructions, such as street vendors and motorbike parking, which are particularly relevant in Da Nang. The Safety dimension has four indicators that measure both traffic-related safety and social security to address pedestrian safety in densely populated areas. The Comfort dimension comprises seven indicators, considering sidewalk conditions, noise, and thermal comfort, all of which are critical in Da Nang's hot-humid climate. Lastly, the Pleasurability dimension has four indicators that focus on aesthetic elements, emphasising local context elements such as green spaces and social spaces. In addition, five indicators are incorporated to address overall perceived environmental quality. The complete set of indicators and sources is reported in Table 1.

At the location level, the variable Objective Environmental Quality (OEQ) is measured using 10 indicators (Table 2) that are selectively adapted from a synthesis of audit tools and foundational walkability studies. These items describe the physical structure's context and are prioritised for their significant relevance to Da Nang, Vietnam, particularly in terms of infrastructure management and tropical climate comfort. For instance, the availability of sidewalks is a core indicator of ensuring safe, continuous pedestrian space, an often-missing feature in developing cities. Meanwhile, the presence of trees serves a functional purpose, providing shade and support for walking in hot, humid conditions. These indicators are evaluated through structured on-site observation using a standardised ordinal audit scale.

3.2. Data collection and sampling strategy

This study employs stratified random sampling to cover the major urban areas in Da Nang's central region, allowing for a comprehensive assessment of walkability across diverse spatial and functional contexts. The process began by defining the stratification criteria and subsequently identifying respective sites within each functional category. Six main functional groups were recognised, reflecting Da Nang's role as both an administrative hub and a rapidly growing centre for tourism, education, and commerce. The commercial and service areas encompass shopping streets, office corridors, and retail complexes that accommodate varied pedestrian intensities and spatial layouts. Coastal tourism and accommodation zones include beachfront walkways, coastal parks, and tourism service precincts, areas that experience heavy pedestrian flow linked to leisure and hospitality activities. Education, healthcare, and public service sectors were

Table 1
Individual-level variable attributes.

Category	Code	Variable	Statement	Source
Accessibility	A1	Public transport accessibility	Public transport stops are conveniently accessible from this sidewalk.	Jahan et al. (2020), Allirani et al. (2024) and Jehle et al. (2024)
	A2	Services accessibility	Services (shopping/dining) are conveniently accessible from this sidewalk.	
	A3	Vender encroachment	Pedestrian areas are free from street vendor occupation.	
	A4	Advertising boards	Pedestrian areas are free from advertising boards.	
	A5	Motorbike parking	Pedestrian areas are free from parked motor vehicles.	
	A6	Temporary encroachment	Pedestrian areas are unobstructed by temporary encroachments (e.g., potted plants).	
Safety	S1	Traffic volume	Traffic near this sidewalk is light and manageable.	Khder et al. (2016), Labdaoui et al. (2021) and Saadi et al. (2022)
	S2	Perceived traffic speed	Vehicles travel at moderate and safe speeds near this sidewalk.	
	S3	Perceived security	Security is well-maintained through cameras, guards etc.	
	S4	Crossing ease	Road crossings near this sidewalk are safe and convenient.	
Comfort	C1	Surface condition	Sidewalk surfaces are smooth and free from cracks or holes.	Abastante et al. (2020), Labdaoui et al. (2021) and Saadi et al. (2022)
	C2	Sidewalk slope	The sidewalk slope is appropriate for walking	
	C3	Surface material	The sidewalk is made with appropriate surface materials.	
	C4	Curb ramps	Curb ramps are present and properly sloped.	
	C5	Noise level	Noise level is acceptable for a comfortable walk	
	C6	Cleanliness	The sidewalk is clean and well-maintained.	
	C7	Thermal comfort	The thermal comfort in this area makes walking pleasant.	
Pleasurability	P1	Visual appeal	The walking environment is visually appealing.	Labdaoui et al. (2021) and Saadi et al. (2022)
	P2	Green spaces	Parks or green spaces are present along this sidewalk.	
	P3	Architectural element	The sidewalk features visually appealing landmarks, street art, or cultural elements.	
	P4	Social spaces	Social spaces, such as cafés and dining areas, are available along the sidewalk.	
Perceived environmental quality (PEQ)	E1	Walking pleasantness	Walking in this area is a pleasant experience.	Saadi et al. (2022) and Service Public Fédéral Mobilité et Transports (2023)
	E2	Public space usage	Public spaces along the sidewalk support sitting, socialising, and recreational activities.	
	E3	Motor traffic disruption	Motor traffic has minimal impact on noise, air quality, and pedestrian comfort.	
	E4	Suitability for vulnerable groups	The sidewalk effectively supports those with strollers, children, or mobility challenges.	
	E5	Walking encouragement	This place effectively encourages walking.	

Table 2
Objective environmental quality attributes.

Code	Variable	Description	Source
O1	Sidewalk availability	Presence of sidewalks on both sides of the street, considering continuity and accessibility.	Horacek et al. (2012), Zhai and Baran (2017), Shaaban (2019) and Labdaoui et al. (2021)
O2	Sidewalk width	Physical width of pedestrian pathways.	
O3	Crosswalk quality	Placement, and presence of traffic controls at pedestrian crossings.	
O4	Number of lanes	Total number of vehicular lanes on the street.	
O5	Posted speed limit	Regulated vehicle speed along the street.	
O6	Street lighting	Extent of lighting infrastructure along the street.	
O7	Garbage bin availability	Extent of garbage cans along the sidewalk.	
O8	Bench availability	Extent of benches along the sidewalk.	
O9	Tree presence	Extent of trees along the sidewalk.	
O10	Adjacent water body	Existence of adjacent water features such as rivers, ponds, or seas.	

represented by universities, hospitals, and government buildings, highlighting pedestrian access to essential facilities. The residential category covers both long-established neighbourhoods characterised by narrow and partially obstructed sidewalks and newly developed districts with upgraded pedestrian infrastructure. Transportation infrastructure sites, comprising major bus terminals, railway stations, and heavily trafficked intersections, provide insight into pedestrian circulation around critical mobility nodes. Finally, urban landscapes and public spaces, such as city parks, plazas, promenades, and riverfronts, illustrate the recreational and aesthetic dimensions of walkability. In total, five sites were selected for each category, resulting in 30 study areas (as illustrated in Fig. 3), thereby capturing a representative spectrum of built environments and pedestrian experiences within Da Nang.

The data collection is carried out from February to August, 2025. Assessment forms, including observation audit forms and survey questionnaires, were developed in English, translated into Vietnamese, and then back-translated for semantic equivalence. For the observation audit, the study refers to the PEDS guideline (Clifton et al., 2007) and the Microscale Audit of Pedestrian Streetscapes (MAPS) (Cain et al., 2014) for a segment-based audit, with 100 m on each street side. Every location is measured in two-segment proportions to independently measure both sides, producing four evaluation records. Sample-size adequacy was evaluated separately at the location and individual levels. At the location level, we drew on the simulation evidence of Maas and Hox (2005), who report that 30 groups are sufficient for unbiased fixed-effect estimates; we accordingly adopt 30

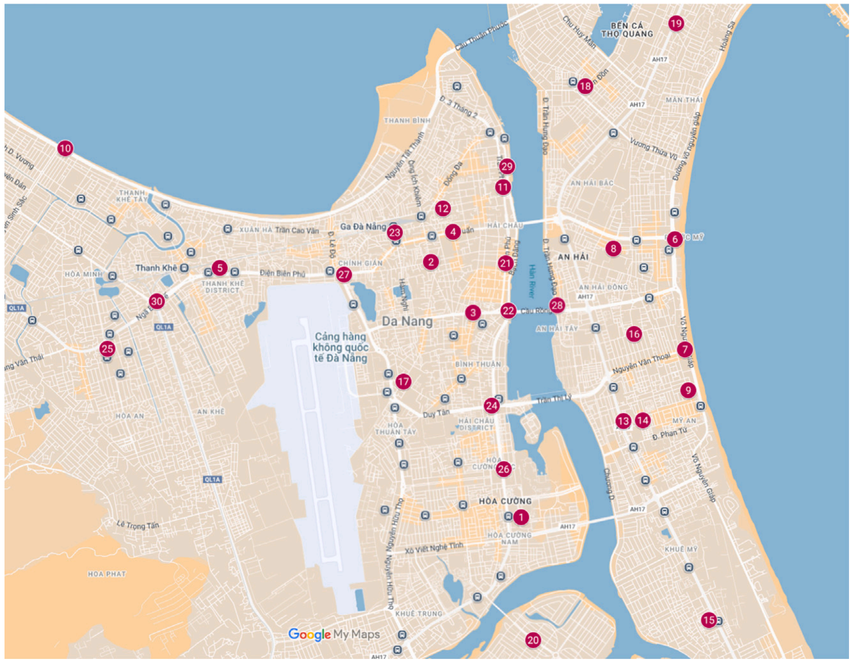

Fig. 3. Map of the 30 study locations.

locations as a deliberate lower-bound design. The within-cluster size (mean = 24) substantially exceeds the conventional 5–10 minimum for stable level-1 estimation (Snijders & Bosker, 2012). The resulting individual-level sample of 720 respondents exceeds the 20:1 indicator-to-respondent ratio recommended for SEM (Hair et al., 2019), which implies a minimum of 520 respondents for the 26 subjective indicators.

A pilot test is also conducted at six sites, engaging 30 participants in completing the survey and providing feedback. Revisions have been implemented to improve the quality of the questions and the reliability of the scale measurements. After data screening, the valid results from 720 participants are used for analysis. The observed demographic profile reflects the on-site sampling design, in which pedestrians were intercepted directly at street locations during peak walking hours. From Table 3, the survey sample is generally young, female, and well educated. To be exact, about 67.4% are aged 30 years or below, while around 72.6% of the sample have a College/University degree or higher. Females make up 55.3% of the group. In terms of economic conditions, most are in the lower to mid range, as around 67.5% earn 10 million VND or less per month. Regarding the influence of health status on walking, 68.3% of respondents reported a moderate or greater impact, whereas the remaining 31.7% reported a slight or negligible impact. Despite this, an overwhelming 86.4% report being able to walk for more than five minutes. Despite using an on-site pedestrian survey, the sample still captures key demographic characteristics of Da Nang, such as a youthful age distribution and a moderate income level.

Table 3
Descriptive statistics of respondents.

Criterion	Characteristics	Number	%
Gender	Male	322	44.7
	Female	398	55.3
Age	30 years old or below	485	67.4
	Above 30 years old	235	32.6
Education	High school or below	197	27.4
	College/University	432	60.0
	Postgraduate Education	91	12.6
Income	Less than 5 million	294	40.8
	5–10 million	192	26.7
	10–20 million	162	22.5
	More than 20 million	72	10.0
Health problem	Slightly or not at all	228	31.7
	Moderately	424	58.9
	Severely	68	9.4
Walk for more than 5 min	Yes	622	86.4
	No	98	13.6

3.3. Data analysis

The use of SEM is well-established in transport-mode adoption research in the Global South (Baig et al., 2024; Basheer et al., 2025). The present study extends this methodological tradition to walkability research through MSEM. Three considerations motivate the choice of MSEM over single-level SEM. First, the data are structurally hierarchical, with 720 individuals nested within 30 locations. Single-level SEM applied to such data violates the independence assumption, deflating standard errors and inflating Type-I error rates (Snijders & Bosker, 2012). Second, the substantive question requires modelling variables that exist at different analytical levels: OEQ is a property of the location, while perceptions are a property of the individual. Single-level SEM forces the analyst to either disaggregate location-level data to individuals (atomistic fallacy) or aggregate individual perceptions to the location mean (ecological fallacy), both of which bias coefficients (Diez Roux, 2002).

MSEM is employed using Mplus 8.3 to examine relationships at both the individual (within-level) and location (between-level) levels (Muthén, 1994). This approach allows the simultaneous estimation of measurement and structural models while properly accounting for the hierarchical nature of the data (Preacher et al., 2010). The data analysis proceeds in four sequential stages. First, intra-class correlations (ICCs) are computed to assess the degree of clustering across locations and confirm the suitability of a multilevel modelling framework. Second, an Exploratory Factor Analysis (EFA) is conducted to identify the underlying latent structure of the measurement scales, and items with low or cross-loadings are removed. Building on these results, the third stage involves conducting a Multilevel Confirmatory Factor Analysis (MCFA) to validate the factor structure and assess construct validity simultaneously at both within- and between-levels. Finally, the refined model is extended to a full MSEM framework to estimate and test

Table 4
Intra-class correlation coefficients.

	E1	E2	E3	E4	E5
ICC	0.744	0.658	0.667	0.656	0.666

the hypothesised structural relationships across levels of analysis. The present study adopts a random-intercept-only specification because the theoretical hypotheses concern main effects of OEQ and individual-level perceptions, not their cross-level moderation; and the present design (with 30 location clusters averaging 24 respondents per cluster) is well-suited to estimating these main effects at both analytical levels, while the reliable estimation of cross-level slope variances generally benefits from larger cluster samples (Snijders & Bosker, 2012).

The model is estimated using the WLSMV estimator under TYPE = TWOLEVEL. This combined specification addresses the principal assumption-related robustness concerns: WLSMV is the recommended estimator for ordinal Likert indicators and is robust to observed-data non-normality (Muthén & Muthén, 2017) while TWOLEVEL directly models the hierarchical nesting of individuals within locations and yields consistent estimates and correct standard errors at both analytical levels (Snijders & Bosker, 2012).

The within-level slope coefficients (β) of the MSEM are estimated from individual-level deviations around cluster means rather than from absolute mean levels (Snijders & Bosker, 2012). This property makes the substantive structural conclusions robust to mean-level demographic shifts in the sample composition: shifts in the sample's demographic profile can affect intercept estimates but do not bias the within-level slopes that constitute the principal findings.

4. Results and discussion

4.1. Preliminary analysis: justification for multilevel modelling

The Intra-class correlation coefficient (ICC) is computed for all indicators of the Perceived environmental quality, which is modelled at both levels, to determine the proportion of variance attributable to location-level differences. As shown in Table 4, all ICC values ranged from 0.656 to 0.744, exceeding the recommended threshold of 0.05 (Snijders & Bosker, 2012), indicating meaningful between-group variance attributable to location-level factors. These findings strongly justify the use of multilevel analysis by confirming the presence of contextual effects.

4.2. Exploratory factor analysis (EFA)

To uncover the underlying factor structure, EFA is conducted using principal axis factoring with varimax rotation. EFAs are applied separately for the survey and observation items.

4.2.1. Survey indicators

The component extraction for the within-level independent indicators reveals that they can be grouped into four subgroups: Accessibility, Safety, Comfort, and Pleasurability. This is consistent with the WNH's theoretical framework. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy is 0.967, indicating a high level according to Kaiser's classification, and Bartlett's Test of Sphericity is significant (Chi-Square = 12215.05, df= 210, $p < 0.001$), indicating that the data are factorable.

As shown in Table 5, all indicators demonstrated strong and unambiguous factor loadings on a single factor, ranging from 0.570 to 0.819, thus exceeding the acceptable threshold of 0.50 (Hair et al., 2019). No substantial cross-loadings are observed in the final solution, supporting a clean and interpretable factor structure. The four extracted factors accounted for 68.12% of the total variance, exceeding the 50% threshold, indicating a satisfactory level of explained variance (Hair et al., 2019).

The dependent variable, PEQ, also loaded onto a single dominant factor, explaining 68.90% of the variance. Factor loadings ranged from 0.731 to 0.960, indicating strong item convergence. The KMO measure of sampling adequacy is 0.871, and Bartlett's test of sphericity is statistically significant ($p < 0.001$), indicating that the data are suitable for factor analysis.

In addition, internal consistency reliability is assessed using Cronbach's alpha, with values of 0.70 or higher considered acceptable (Hair et al., 2019). All five constructs met this criterion, indicating satisfactory internal reliability. Therefore, the survey scale demonstrates adequate validity and is appropriate for subsequent analysis.

4.2.2. Observation indicators

Exploratory factor analysis of indicators O1–O10 yielded a single factor, termed OEQ (Table 6). Items O5 and O10 are excluded due to low factor loadings (<0.4) to improve construct clarity and unidimensionality. The remaining items demonstrated high loadings (0.657–0.756), exceeding the 0.50 threshold (Hair et al., 2019). The KMO measure is 0.804, and the total variance explained is 53.19%, indicating suitability for further analysis. Cronbach's alpha for the retained items is 0.896, confirming acceptable internal consistency. This empirically supports the unidimensional reflective specification of OEQ argued on theoretical grounds.

4.3. Multilevel structural equation modelling (MSEM) analysis

4.3.1. Measurement model evaluation and structural model fit

To validate the multilevel measurement model, MCFA is performed, capturing both within-level (individual) and between-level (location) structures. This two-level approach is essential to confirm whether the factor structure identified in EFA is invariant across individual and contextual levels (Geldhof et al., 2014). The within-level model consisted of five latent constructs: Accessibility, Safety, Comfort, Pleasurability, and PEQ. At the between-level, two constructs are assessed: OEQ and PEQ.

As the results showed in Table 7, all factor loadings exceeded the threshold of 0.5 and were statistically significant ($p < 0.001$) (Hair et al., 2019), confirming that the observed items effectively represented their respective latent factors. Convergent validity is established, with all constructs exhibiting average variance extracted (AVE) values above 0.5 and composite reliability (CR) above 0.7 (Fornell & Larcker, 1981).

Model fit indices indicated good fit across both levels: $\chi^2/\mathrm{df} = 2.67$, RMSEA = 0.048, $\mathrm{SRMR}_{\mathrm{within}} = 0.028$, $\mathrm{SRMR}_{\mathrm{between}} = 0.068$, CFI = 0.959, and TLI = 0.953. These results meet widely accepted thresholds for satisfactory model fit (Hu & Bentler, 1999). These findings support the internal consistency and construct validity of the model at both individual and contextual levels, confirming its suitability for subsequent multilevel analyses (Geldhof et al., 2014).

4.3.2. Structural model assessment and hypothesis testing

MSEM is used to test the hypothesised relationships at both the within- and between-levels. This method combines the strengths of structural equation modelling and multilevel modelling to simultaneously account for measurement error and nested data structures (Preacher et al., 2010). The model comprises a within-level component that assesses individual-level perceived predictors and a between-level component that examines the influence of OEQ on PEQ.

As shown in Fig. 4 and Table 8, all five estimated paths are statistically significant ($p < 0.001$), providing empirical support for the proposed multilevel framework. Accordingly, H1–H5 are all supported. These findings affirm the utility of MSEM in capturing both contextual and individual-level determinants of PEQ, offering a comprehensive understanding of how objective and subjective factors jointly shape environmental perception (Muthén, 1994; Preacher et al., 2010).

Table 5
Results of EFA for survey indicators.

Independent variables					Dependent variable	
	Accessibility	Safety	Comfort	Pleasurability	PEQ	
A4	0.722				E5	0.960
A3	0.715				E1	0.847
A6	0.660				E4	0.808
A5	0.652				E2	0.786
A2	0.646				E3	0.731
A1	0.620					
S2		0.719				
S4		0.670				
S1		0.586				
S3		0.570				
C5			0.819			
C4			0.749			
C2			0.739			
C3			0.708			
C1			0.703			
C7			0.689			
C6			0.582			
P1				0.752		
P3				0.722		
P2				0.598		
P4				0.589		
Cronbach's alpha	**0.918**	**0.882**	**0.941**	**0.890**	**0.913**	

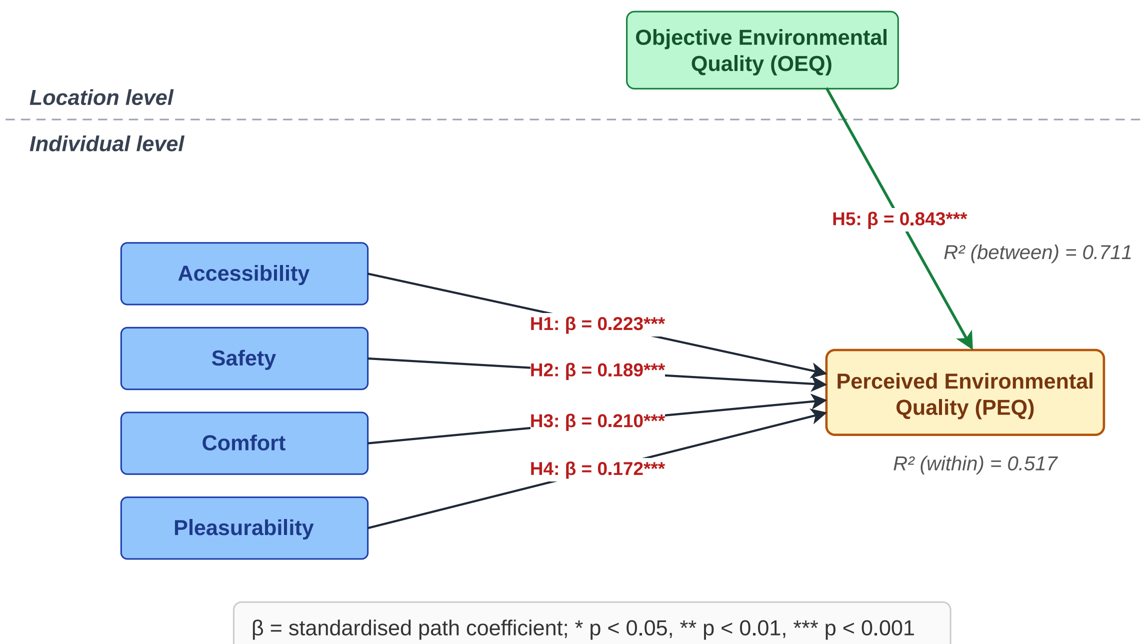

Fig. 4. Model's results.

Table 6
Results of EFA for observation indicators.

	OEQ	Total variance	Cronbach's alpha
O6	0.756	53.19%	0.896
O4	0.754		
O9	0.753		
O8	0.749		
O1	0.735		
O3	0.714		
O7	0.709		
O2	0.657		

Within-level

At the within-level, the construct Accessibility had the most potent positive effect on PEQ ($\beta = 0.223$), followed by Comfort ($\beta = 0.210$), Safety ($\beta = 0.189$), and Pleasurability ($\beta = 0.172$). The model explained 51.7% of the variance in PEQ ($R^2 = 0.517$), indicating a substantial contribution of individual-level predictors. These results confirm the statistical significance of all hypothesised within-level paths, with the relative magnitudes read as descriptive effect sizes. Accessibility shows the largest standardised effect, in line with its foundational position in the Walking Needs Hierarchy. More notable is the comparatively strong effect of comfort, which exceeds that of safety. This prominence likely reflects the salience of physiological stressors, chiefly thermal load and noise: where the constant presence of motorcycle traffic normalises acute traffic threats, such stressors come to weigh more heavily in how the walking environment is perceived. This reading is consistent with environmental-psychology accounts of stress and restoration (Kaplan & Kaplan, 1989) and with the emerging debate on thermal walkability in hot-humid contexts (Lai et al., 2019; Wang et al., 2022). More

Table 7
Measurement model evaluation using MCFA.

Within level				Between level			
	Estimates	S.E.	P-value		Estimates	S.E.	P-value
PEQ	**AVE = 0.504; CR = 0.835**			**PEQ**	**AVE = 0.763; CR = 0.942**		
E1	0.718	0.015	0.000	E1	0.913	0.043	0.000
E2	0.696	0.013	0.000	E2	0.846	0.069	0.000
E3	0.696	0.017	0.000	E3	0.837	0.083	0.000
E4	0.663	0.015	0.000	E4	0.851	0.064	0.000
E5	0.772	0.007	0.000	E5	0.918	0.034	0.000
Accessibility	**AVE = 0.656; CR = 0.919**			**OEQ**	**AVE = 0.525; CR = 0.898**		
A1	0.823	0.008	0.000	O1	0.713	0.095	0.000
A2	0.835	0.010	0.000	O2	0.747	0.120	0.000
A3	0.783	0.011	0.000	O3	0.723	0.087	0.000
A4	0.879	0.008	0.000	O4	0.694	0.119	0.000
A5	0.753	0.008	0.000	O6	0.707	0.110	0.000
A6	0.779	0.010	0.000	O7	0.725	0.085	0.000
Safety	**AVE = 0.658; CR = 0.884**			O8	0.739	0.080	0.000
S1	0.837	0.009	0.000	O9	0.746	0.078	0.000
S2	0.860	0.009	0.000				
S3	0.829	0.010	0.000				
S4	0.710	0.014	0.000				
Comfort	**AVE = 0.693; CR = 0.940**						
C1	0.834	0.008	0.000				
C2	0.767	0.011	0.000				
C3	0.823	0.009	0.000				
C4	0.838	0.008	0.000				
C5	0.872	0.005	0.000				
C6	0.817	0.008	0.000				
C7	0.873	0.006	0.000				
Pleasurability	**AVE = 0.676; CR = 0.893**						
P1	0.813	0.009	0.000				
P2	0.803	0.012	0.000				
P3	0.839	0.009	0.000				
P4	0.834	0.011	0.000				

Table 8
Structural path coefficients using MSEM.

	Within level			Between level		
	Estimates	*P*-value	Result	Estimates	*P*-value	Result
H1: Accessibility → PEQ	0.223	0.000	Supported			
H2: Safety → PEQ	0.189	0.000	Supported			
H3: Comfort → PEQ	0.210	0.000	Supported			
H4: Pleasurability → PEQ	0.172	0.000	Supported			
H5: OEQ → PEQ				0.843	0.000	Supported

broadly, in such settings, physiological comfort stressors shape the walking experience alongside the established concerns of access and safety, rather than displacing them.

Indeed, thermal comfort (C7: Mean = 3.11, FL = 0.873) stands out as the most significant factor, with the highest loading, underscoring the necessity of shade for functional walkability in hot and humid environments. With a similarly high loading, noise level (C5: Mean = 3.12, FL = 0.872) reveals the mental toll of persistent motorcycle noise, underscoring the importance of soundscape quality for perceived Comfort. However, these influential factors are also among the poorest performing (with low mean values), creating a significant comfort deficit. This deficit is compounded by mediocre performance in core comfort indicators, such as surface material (C3) and curb ramps (C4), which are common weaknesses in Da Nang's underdeveloped pedestrian infrastructure. These factors elevate Comfort to a significant concern in cities, making it a baseline requirement. Therefore, to improve walkability, interventions must address these pervasive comfort issues, for instance, by mandating shade cover or implementing traffic-calming measures to reduce noise emissions. However, this comparatively strong role of comfort is best interpreted as a context-specific emphasis within Alfonzo's (2005) Hierarchy of Walking Needs rather than a generalisable theoretical revision: replication across other tropical, motorcycle-dependent cities is required before any broader claim about hierarchy revision can be advanced.

Beyond Comfort's prominent concern, the other dimensions also exhibited distinct characteristics in Da Nang's context. Key accessibility problems, such as sidewalk encroachment by vendors (A3: Mean = 2.80, FL = 0.783) and motorbike parking (A5: Mean = 2.80, FL = 0.753), reflect a widespread challenge. In Da Nang, these activities are deeply ingrained in the street culture, where sidewalks are often used for commercial purposes and parking spaces are scarce. That undermines physical Accessibility but contributes to good service accessibility (A2: Mean = 3.50, FL = 0.835), representing a clear trade-off between unobstructed pedestrian pathways and the informal street economy. The accessibility-vending-parking trade-off observed in our data resonates with recent literature on negotiated public space (Kamalipour & Peimani, 2019; Dovey & Recio, 2024), which cautions against blanket regulatory crackdowns and advocates for time-bounded, zoned management that preserves the vitality of informal street economies while restoring continuous pedestrian flow.

Although Safety is perceived as slightly less influential overall, it remains a significant concern. While perceptions of general traffic are moderately acceptable, perceived speed (S2: Mean = 3.50, FL = 0.860) and traffic volume (S1: Mean = 3.38, FL = 0.837) are overshadowed by a critical failure in a fundamental aspect of pedestrian safety: crossing ease (S4: Mean = 2.97, FL = 0.710). This highlights the need for targeted improvements in traffic control and intersection design. In Da Nang, the overwhelming presence of motorcycles, which often ignore pedestrian priority at crosswalks, further intensifies safety risks. Ultimately, these conditions reflect a systemic failure to prioritise pedestrian needs, creating a substantial obstacle to the creation of safe walking environments.

Pleasurability, the least influential factor overall, falls within a narrow mid-range (3.20–3.38), reflecting a solid but unremarkable aesthetic foundation. Architectural elements (P3: Mean = 3.24, FL = 0.839) combine the highest perceptual weight with a near-lowest mean, marking them as the prime intervention target. Visual appeal (P1: Mean = 3.20, FL = 0.813) records the lowest mean overall, signalling the most visible aesthetic weakness. By contrast, social spaces (P4: Mean = 3.38, FL = 0.834), which combine high leverage with the best current performance, warrant preservation, while green spaces (P2: Mean = 3.32, FL = 0.803) have the lowest factor loading and require only sustained upkeep. Consolidating architectural-landmark presence and strengthening visual appeal could elevate Da Nang's walkability from merely functional to truly enjoyable.

Between-level

At the between-level, there is a strong location-level association of OEQ with PEQ ($\beta = 0.843$, $p < 0.001$). The model accounted for a substantial proportion of variance, with $R^2 = 0.711$, indicating that 71.1% of the variation in PEQ across locations is attributable to differences in objectively measured built environment features. This pattern aligns with arguments that micro-mobility infrastructure is the binding constraint on walkability in Global-South contexts (Pojani & Stead, 2015), and that physical upgrades (sidewalk width, shading) can produce disproportionate gains in perceived quality.

An analysis of OEQ indicators reveals clear strategic priorities for urban intervention. The two most influential factors are Sidewalk width (O2, FL = 0.747) and Tree presence (O9, FL = 0.746). However, their current implementation is suboptimal, with O2 showing a relatively low mean score (Mean = 2.97) and O9 a moderate one (Mean = 3.23). This presents a high-impact opportunity, where targeted interventions to widen sidewalks and increase tree cover are likely to yield significant improvements in perceived quality. Furthermore, fundamental pedestrian infrastructure elements, including Sidewalk availability (O1, Mean = 2.73) and Crosswalk quality (O3, Mean = 2.77), also emerge as critical concerns. Although both show the lowest mean scores, they maintain relatively high factor loadings, indicating that these deficiencies substantially drag down overall quality assessments and require urgent remedial action.

Conversely, the indicators with the highest performance scores, namely Number of lanes (O4, Mean = 3.47) and Street lighting (O6, Mean = 3.50), exhibit the lowest factor loadings (O4 FL = 0.694; O6 FL = 0.707) among all measured items. This combination suggests that, while these elements are currently well provided, they contribute less strongly to the overall construct of environmental quality. Consequently, a maintenance-focused approach rather than additional investment is recommended for these attributes.

4.4. Additional location-based disparities

This part involved comparing mean scores of PEQ, OEQ, and four subjective experience dimensions across different functional zones. As shown in Fig. 5, PEQ scores remain moderate across all six location groups, indicating general public acceptance but highlighting a lack of highly valued environments. The areas of Coastal tourism & accommodation (3.33) and Urban landscape & public spaces (2.98) scored highest, suggesting that aesthetically appealing, recreational areas are better perceived. In contrast, essential service-oriented zones like Commercial & service (2.29) and Education, healthcare & public services (2.48) received the lowest PEQ scores, indicating dissatisfaction with frequently used utilitarian spaces. The OEQ scores largely reflect this trend, as the same two leisure-focused zones received the highest scores (3.59 and 3.54), confirming a prioritisation of investment in areas that contribute to city branding. Meanwhile, foundational living and service zones, including Education, healthcare, & public services (2.63) and Residential areas (2.76), remain under-resourced, despite their importance for daily life. Notably, Commercial & service areas exhibit a significant perception gap, ranking third in OEQ but lowest in PEQ. This underscores that measurable quality alone cannot ensure positive public perception, emphasising the influential role of subjective experience in environmental evaluation.

Fig. 6 further illustrates pedestrian perceptions across four key dimensions: Accessibility, Safety, Comfort, and Pleasurability. Coastal tourism & accommodation consistently ranked highest across all four dimensions, particularly in Safety (3.97) and Pleasurability (3.73), solidifying its status as a positively experienced environment. Urban landscape & public spaces also performed well in Comfort (3.54) and Pleasurability (3.64), reinforcing their contribution to urban livability. The severe disconnect between OEQ and PEQ in the Commercial & service areas can be explained by these detailed metrics. This zone scored lowest across the board, especially in Comfort (2.71) and Safety (2.81), revealing that despite potentially solid infrastructure investment, the actual user experience is characterised by discomfort and safety concerns, which drastically depresses the overall perception. Moreover, these results also reveal specific issues for other zones. Education, healthcare, & public services had the lowest Accessibility (2.63), pointing to barriers in reaching essential services. Residential areas performed moderately but showed a deficit in Comfort (2.94). Notably, Transportation infrastructure has a low Accessibility score (2.94), even though it should be a high-performing domain, underscoring mobility challenges.

The analysis demonstrates that walkability is shaped not only by land-use typologies but also by localised user experience. Misalignment between infrastructure quality and pedestrian experience, particularly in essential service areas, suggests that physical upgrades alone are insufficient. A balanced urban policy should prioritise not just the visible urban fronts, but also the fundamental human-centric needs of everyday environments that are critical to citizens' well-being.

5. Conclusion

This study develops and verifies an integrated MSEM framework that accounts for the unique circumstances of tropical, motorcycle-dominated cities. Its contribution is threefold: methodologically, by operationalising MSEM to integrate subjective and objective walkability indicators at their respective analytical levels; theoretically, by providing an empirical multilevel test of the Hierarchy of Walking Needs in such a setting and by identifying a context-specific emphasis on comfort; and empirically, by generating fine-grained evidence on micro-scale stressors in a Global-South city.

At the individual level, MSEM corrects for inflated associations by controlling for contextual variance. This purification process ensures that the within-level coefficients accurately reflect genuine individual psychological processes. Our findings thus reveal that an individual's perceptions, relative to others in the same environment, distinctly shape their evaluations. Ranked by standardised coefficient, the within-level needs are ordered as Accessibility, Comfort, Safety and Pleasurability. The data are consistent with the foundational role of accessibility within the WNH. At the same time, the comparatively high standing of comfort, driven largely by thermal and noise stressors, is a context-specific emphasis that warrants replication across other tropical, motorcycle-dependent cities. This emphasis suggests that in a hot, humid, and motorcycle-saturated environment, physiological stressors such as thermal load and noise can weigh as heavily as traffic safety in shaping pedestrian perception. Additionally, the strong influence of Accessibility validates its foundational role, yet its manifestation in Da Nang is uniquely tied to the negotiation of informal encroachments, such as vendor and motorbike parking.

At the location level, MSEM isolates an actual contextual effect. A single-level model would have erroneously treated the contextual variable as an individual-level attribute, resulting in model misspecification. In contrast, our MSEM effectively models objective environmental

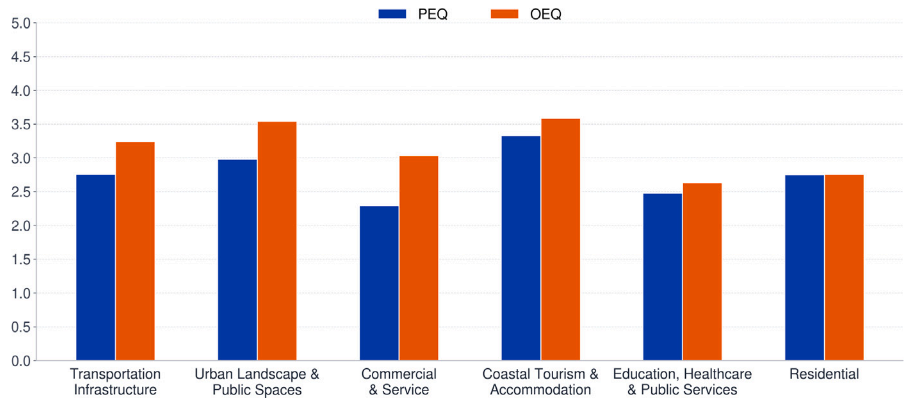

Fig. 5. Mean scores of environmental quality by location group.

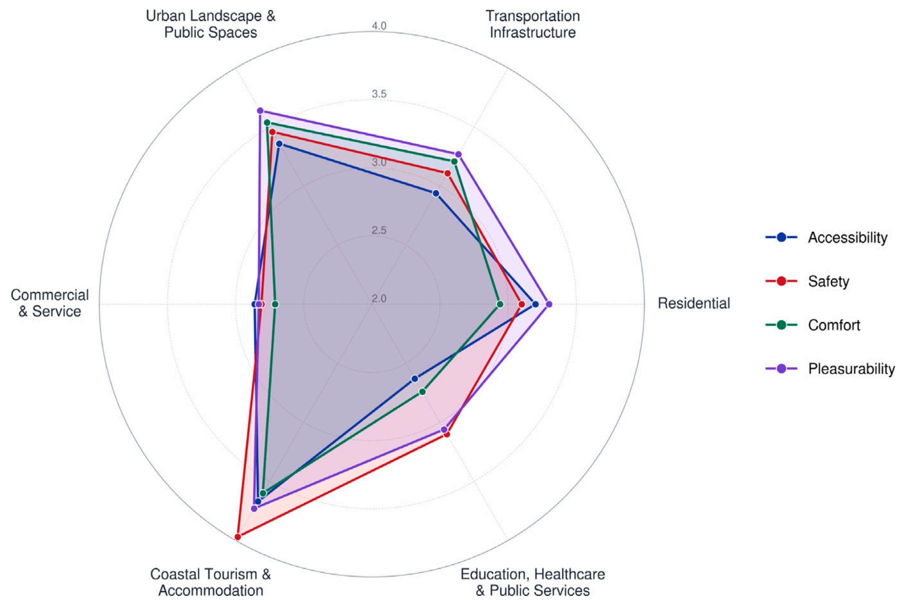

Fig. 6. Multidimensional walkability profiles by location group.

quality as a group-level construct, demonstrating its powerful and direct effect on aggregate perceptions. This finding powerfully reinforces that investments in tangible infrastructure, particularly sidewalk width and tree presence, are not merely cosmetic but fundamentally reshape the collective perception of a neighbourhood. This model indeed allows for the positioning of individuals within the spatial context of their neighbourhoods and systematically models inter-neighbourhood differences. In addition, a mean comparison across functional urban zones offers complementary insights. Notably, areas related to essential services, which form the backbone of a functional environment, had significantly lower walkability than areas related to iconic landmarks.

The results provide policy guidelines for Da Nang and other cities alike. The strong association between objective and subjective measures observed at the between-level provides empirical grounding for prioritising physical interventions. The recommendations were organised as a three-tier framework, crossing expected impact (magnitude of within- and between-level coefficients; across-location performance gaps) with implementation horizon, and differentiated by location group.

- Tier 1. High-impact, immediate (citywide habitability). Thermal comfort and noise reduction are imperative. Urban planning should mandate permanent shading through continuous tree canopies or arcades and deploy traffic-calming measures to suppress noise. Sidewalk accessibility must be restored not through strict enforcement but through time-window vending zones and designated motorbike parking pockets. These instruments balance pedestrian movement with the street vitality intrinsic to Da Nang's urban life.
- Tier 2. High-impact, structural (zone-targeted infrastructure). Capital-intensive investments, namely continuous sidewalk widening and protected pedestrian crossings, should be allocated to the essential-service corridors (Commercial & service; Education, healthcare & public services), where mean perceived environmental quality is lowest and where accessibility and comfort deficits are most pronounced.
- Tier 3. Lower-impact, context-specific (maintenance and enhancement). In Coastal tourism & accommodation and Urban landscape & public spaces zones, marginal resources should target pleasurability rather than fundamental restructuring, prioritising architectural-landmark consolidation and visual-appeal upgrades, which combine high perceptual leverage with weak current performance. Social spaces should be preserved at their current high

level, while green spaces, lighting, and lane provision require only routine upkeep, given their modest marginal contribution.

This evidence-based, tiered, and zone-differentiated framework treats physical interventions as expected to translate into perceptual improvements; causal verification will require longitudinal or natural-experiment designs.

This study makes a meaningful contribution to the walkability literature, but some limitations remain to be addressed. While focusing on Da Nang offers valuable contextual insights, it certainly lacks generalisability. Hence, the proposed approach should be tested across cities in the Southeast Asian region to recognise the greater variability. Also, the on-site sampling design over-represents respondents with formal qualifications relative to the city profile, which bounds the descriptive interpretation of mean-level estimates. Future waves should adopt stratified sampling that purposively reaches underrepresented segments to strengthen the external validity of mean-level estimates. In addition, although it is defined as a critical parameter, thermal comfort is evaluated solely on personal perceptions. The lack of physiological or real-time data for thermal comfort limits behavioural interpretation. Future research could utilise wearable sensors, GPS tracking devices, and ethnographic walking interviews to deepen the understanding of causal relationships. Furthermore, several plausibly relevant covariates were not measured: at the individual level, trip purpose and prior familiarity with the location; at the location level, land-value gradients, policing intensity, and variation in pedestrian-flow intensity. These should be included in subsequent waves. Additionally, no separate post-hoc robustness analyses (e.g., alternative subsamples, alternative cluster definitions, bootstrap re-estimation) were conducted in the present study; such analyses represent a target for future replications. While the number of clusters (n = 30) is sufficient for unbiased fixed-effect estimation (Maas & Hox, 2005), the exploration of cross-level interaction effects represents a valuable direction for future replications with larger location samples (Snijders & Bosker, 2012). In addition, the single-factor reflective specification of OEQ adopted here, though theoretically grounded and empirically supported in our data, should be tested against richer alternative specifications, such as higher-order structure. The descriptive comparison of the within-level effects, in turn, could be complemented by formal coefficient-difference tests within the same confirmatory framework. Both refinements would benefit from larger samples spanning additional locations and cities.

In conclusion, this research goes well past the diagnosis of walkability problems to provide an established hierarchical framework for intervention. By establishing the context-sensitive refinement of pedestrian needs and by measuring the tangible effects of the urban environment, this research provides a scientifically supported roadmap for navigating the intricate task of walkability. This proposed framework is scalable and adaptable, particularly for rapidly developing cities in the Global South with increasing motorised transport.

CRediT authorship contribution statement

Nguyet-Phuong Ta: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Richa Maheshwari:** Writing – review & editing, Supervision, Conceptualization. **Son-Tung Nguyen:** Writing – review & editing, Validation, Data curation, Conceptualization. **Mario Cools:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing 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.

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