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Ten questions concerning thermal comfort in transient spaces in the built environment

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ABSTRACT

Thermal comfort in transient indoor spaces, such as transportation terminals, waiting areas, and building lobbies, presents a growing challenge in the built environment. Characterized by fluctuating thermal conditions, short dwell times, and limited occupants' access to environmental control, these spaces cannot be adequately served by conventional steady-state comfort models. Existing literature is fragmented across disciplines, methodologies, and definitions, limiting transferability of findings and operational strategies. This paper addresses that gap through a ten-question synthesis, identifying challenges, opportunities, and future research directions. It proposes a working definition of indoor transient spaces as spatial zones characterized by reduced or absent occupants' access to environmental control, combined with: (a) designed for short dwell time — configured for limited-duration occupancy as part of a single visit rather than sustained use, and/or (b) transitional spatial function — serving principally to connect or mediate between thermally or functionally distinct zones. It further identifies that these characteristics afford designers more flexibility than non-transient environments permit: occupants tolerate broader thermal ranges, and phenomena such as alliesthesia can transform thermal transitions into positive sensory experiences. With existing comfort models proving inadequate for transient conditions, the paper highlights more suitable approaches from passive architectural interventions and function-specific comfort criteria to dynamic, data-driven control systems supported by AI and Digital Twin technologies. Finally, it maps the interdisciplinary scope this research demands, calling for a Transient Comfort Index integrating physiological, behavioural, and environmental variables. Realizing this potential will require the technical advances and definitional clarity this paper works to establish.

1. Introduction

Thermal comfort research in the built environment has traditionally focused on indoor spaces where occupants dwell for sufficient durations to permit stable thermal and physiological conditions to be assumed (e.g., offices and residential buildings). However, a growing body of research has identified a distinct category of spaces— referred to variably as “non-uniform,” “transitional,” or “transient”- that do not satisfy the environmental and occupant criteria upon which conventional

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Nomenclature

PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
Met	Metabolic Rate (met)
Clo	Clothing Insulation (clo)
PCS	Personal Comfort Systems
TSENS	Thermal Sensation model (Gagge)
MTV	Mean Thermal Vote model (Nilsson)
DTS	Dynamic Thermal Sensation model (Fiala)
TS	Thermal Sensation model (Zhang)
TSV	Thermal Sensation Vote model (Takada)
DMV	Dynamic Mean Vote model (Vellei)
JOS-3	Joint System Thermoregulation Model, version 3
HVAC	Heating, Ventilation, and Air Conditioning
MRT	Mean Radiant Temperature
VAV	Variable Air Volume
MPC	Model Predictive Control
DRL	Deep Reinforcement Learning
DCV	Demand-Controlled Ventilation
BIM	Building Information Modelling
IoT	Internet of Things
IEA	International Energy Agency
EBC	Energy in Buildings and Communities Programme

comfort models are founded [1,2]. These spaces are characterized by dynamic thermal environments, rapidly changing occupancy profiles, and diverse spatial functions that challenge the assumptions underlying established frameworks such as the Predicted Mean Vote and Predicted Percentage of Dissatisfied (PMV-PPD) model [1]. Spaces such as airport or train terminals, shopping malls, building lobbies, and gymnasium facilities have all been identified as transient in the literature [3,4], yet they share little in common beyond their dynamic nature, reflecting the breadth and ambiguity of the term as it is currently applied.

The inconsistency in terminology across studies and standards has significant implications for the comparability and advancement of thermal comfort research in these spaces. Definitions of transient, transitional, and non-uniform spaces vary considerably: Dahlan and Gital define transient spaces primarily through their environmental conditions [5], while Ghaddar et al. extend the definition to encompass both environmental variability and the unique physiological responses of occupants [6]. Wang et al. characterize transience through the physical relocation of the occupant between two thermally distinct environments [7], whereas Lei et al. associate transient conditions specifically with the transition between naturally ventilated and mechanically conditioned spaces [8]. These contrasting characterizations reflect a broader fragmentation in the field, wherein the absence of widely adopted definitions limits the development and application of appropriate thermal comfort evaluation methods. As the scope of built environment research expands to include indoor-outdoor transitional zones and other dynamic spaces encountered in everyday building use, the need for consistent and precise terminology becomes increasingly critical [9,10].

Beyond definitional challenges, the thermal experience of occupants in transient spaces differs fundamentally from that in non-transient environments, with important consequences for comfort modelling. The dynamic qualities of transient spaces have been shown to strongly influence occupants' thermal sensation: Wu et al. demonstrate that thermal sensation in transient conditions is highly correlated with the rate of change in skin temperature [11], while Velt et al. identify a disproportionately large impact on thermal sensation relative to a comparatively smaller impact on overall thermal comfort [12]. This divergence between sensation and comfort arises in part from the shortened dwell times characteristic of transient spaces- which limit the occupant's capacity for thermal acclimatization—and is due to the body's thermoreceptors, which respond to the rate of skin temperature change rather than its absolute level—producing sensation overshoots that outlast the stimulus itself [13–15]. As Wang et al. describe, occupants experience strong thermal sensations- hot or cold- while still reporting overall comfort, precisely because full acclimatization has not occurred [7]. Conversely, once acclimatization begins, previously tolerated sensations produce discomfort. Pitt et al. further demonstrate that occupants exhibit distinct thermal reactions and expectations depending on the type of transitional space encountered [16]. These findings are reinforced by Hou et al., who report that occupants in transient spaces display higher thermal tolerance and satisfaction rates compared to reference non-transient environments [17]. This difference is compounded by the fact that, unlike in offices or homes, occupants' metabolic rate (met) and clothing insulation (clo)—the two occupant-side inputs on which steady-state comfort models such as PMV-PPD depend—can themselves change sharply within a single visit: walking, standing, or carrying luggage alters met within minutes, while removing or adding a coat at a building entrance alters clo just as quickly, often faster than thermoregulation itself can adjust. These shifts further interact with the mood or affective state associated with different activities—the urgency of rushing to a gate, for instance, differing markedly from the relaxed pace of browsing a shopping mall—compounding the difficulty of specifying stable met and clo inputs for comfort simulation. Collectively, these studies underscore that thermal comfort, sensation, satisfaction, and tolerance operate differently in transient spaces, and that their differentiation is essential for accurate evaluation and modelling.

Despite the growing recognition of these challenges, the field lacks a consolidated framework for investigating thermal comfort in transient spaces. Evidently, the existing literature is fragmented across disciplines, methodologies, and definitions. This fragmentation ultimately limits the transferability of findings and operational strategies. This paper addresses that gap by providing a structured synthesis of current knowledge, organized around ten key questions grouped into four thematic clusters. The first cluster establishes the framing: the definitions of transient spaces in standards and literature (Q1) and the importance of addressing thermal comfort in these spaces (Q2). The second cluster diagnoses the challenges: design obstacles (Q3), occupancy differences between transient and non-transient spaces (Q4), measurement and monitoring difficulties (Q5), and the suitability of existing comfort models (Q6). The third cluster addresses reframing and implementation: design opportunities (Q7) and the role of building technologies (Q8). The fourth cluster provides optimization and future directions: optimization strategies (Q9) and interdisciplinary opportunities for future research (Q10). Through this structure, the paper aims to establish a foundation for more rigorous, comparable, and impactful thermal comfort research in transient spaces. This structured synthesis is itself the paper's core contribution: it converts a fragmented body of literature into a navigable foundation for future design, regulation, and research in transient spaces.

2. Questions and answers

Question 1: How does the thermal comfort literature define transient indoor spaces?

Established in the introduction, transient indoor spaces remain ambiguously defined across disciplines, building regulations, and academic literature, and the absence of a shared definition complicates efforts to model thermal comfort, assess performance, and establish appropriate design or operation strategies. This question examines how

standards and academic research have approached this challenge, and proposes a working definition on that basis.

It is worth clarifying at the outset that the terms "transitional" and "transient," while frequently used interchangeably, refer to conceptually distinct phenomena. "Transitional" carries an architectural meaning, describing spaces defined by their connective or circulatory function such as entrance halls, corridors, or atria, linking zones of different use or climate. "Transient," in contrast, describes the environmental and temporal character of a space, referring to conditions that are dynamic, short in duration, or variable over time. In practice, however, these two dimensions frequently coincide: the spaces most architecturally defined as transitional are also those most likely to exhibit transient environmental conditions. This paper accordingly focuses on spaces where both characteristics overlap, spaces that are at once architecturally transitional in their function and transient in their thermal conditions, and uses the term "transient spaces" to capture this combined meaning throughout.

Across major international standards and guidelines, there is currently no formal definition of "transient spaces." Instead, these documents refer more generally to transient thermal conditions or short-term exposure, usually in the context of the limitations of comfort models such as the PMV-PPD model or adaptive approaches. Table 1 summarizes the treatment of transient conditions across the most relevant standards, including ASHRAE 55 [18], ISO 7730 [19], CIBSE Guide A [20], and GB 50736–2012 [21]. Other widely referenced standards, including BS EN 16798–1 [22], BS EN 15251 [23], ISO 19659-2 [24], CR 1752:1998 [22], and DIN EN ISO 11855-1 [25], provide no definition of transient spaces.

A number of consistent observations emerge from this review. First, none of the major standards provide a spatial typology or formal classification of transient spaces. Second, where transient or non-steady-state conditions are acknowledged, most explicitly in ASHRAE 55 and ISO 7730, the treatment is framed as a limitation of existing comfort models rather than as the basis for dedicated evaluation criteria. Third, the occupancy-related parameters included across standards remain anchored to metabolic rate and clothing insulation, parameters that are difficult to assess reliably in spaces with short, variable dwell times. CIBSE Guide A goes furthest among the standards reviewed, explicitly accounting for occupant dwell time and thermal preference in transient-adjacent zones, though it stops short of a formal typology of transient spaces as a general category [20]. Although the standards reviewed differ in their scope and terminology, they exhibit remarkable consistency in one important respect: none explicitly defines transient indoor spaces as a distinct spatial category. Instead, they primarily recognize transient thermal conditions or short-duration occupancy as situations where conventional thermal comfort assessment have limited applicability. Consequently, current standards regulate transient exposure indirectly through limitations on comfort models rather than through explicit guidance on the design or classification of transient spaces.

Beyond those, the wider international framework including ISO 17772-1 [26] and its accompanying technical guidance, adopts a similar approach by specifying indoor environmental criteria, occupancy categories and local discomfort limits without formally recognizing transient indoor spaces as a distinct spatial typology. Reviews comparing international thermal comfort standards similarly conclude that existing guidance is primarily organized around environmental quality categories and comfort models rather than classifications of building space types [27]. Likewise, building rating systems such as LEED, BREEAM and WELL recognize entrance lobbies, vestibules and buffer spaces for energy efficiency or indoor environmental quality purposes, but do not classify them as a separate thermal comfort space typology.

Evidently, there is a significant missed opportunity in regulation: the integration of a typology of transient zones into standards would allow for more targeted comfort expectations and energy strategies. For example, applying dynamic comfort criteria or adjusted thermal thresholds to these spaces could optimize energy savings while maintaining or improving the occupant experience.

Building on this regulatory gap, academic research has proposed more spatially and physiologically grounded definitions, though without convergence. Pitts [16], De Souza et al. [28], Hou et al. [1] each approach the problem from different angles — architectural function, thermal contrast and exposure intensity, and semi-outdoor conditioning respectively — while Arens et al. [13,14] and Zhang et al. [15] focus specifically on the physiological mechanisms triggered by thermal transitions, including sensation overshoots and delayed adaptation that neither the PMV-PPD nor adaptive models are designed to capture. Taken together, these studies consistently identify the same core characteristics — short dwell times, thermal contrast, limited occupant control, and connective spatial function — while framing them through different disciplinary lenses. It is on this convergent but fragmented basis that the working definition proposed below is grounded.

Despite this fragmentation, the academic literature repeatedly characterizes "transient spaces" through several recurring criteria. These include:

Table 1
Treatment of non-steady-state and transient conditions in selected thermal comfort standards.

Standard	Explicit definition of transient spaces?	Definition and Specifications of Transient / Non-Steady-State	Requirements & Limits	Impact on Comfort Assessment	Illustrative Examples of Transient
ASHRAE 55	No	Defines drifts (passive change) and ramps (active change).	Max change: 1.1 °C in 15 mins; 2.2 °C in 1 h. Cyclic variations must stay within a 1.1 °C peak-to-peak range.	Standard model (PMV-PPD), only applies to occupants in a space for ≥15 mins.	A retail store "cool-down" period after a morning opening or an office "setback" recovery.
ISO 7730	No	Clause 8 specifies transients (step changes) and temperature cycling.	Limits for vertical air temp difference (<3 °C–4 °C) and floor temp (19 °C–29 °C) remain critical constraints during environmental shifts.	Acknowledges "Physiological Lag" where comfort perception not align with instantaneous environment during rapid shifts.	A worker moving from a cold warehouse into a heated shipping office (Step Change).
CIBSE Guide A	No	Employs Adaptive Thermal Comfort (via TM52/TM59) for transient-adjacent zones and naturally ventilated spaces.	Uses Category I, II, III targets. In summer, accepts daily temperature swings up to 8 K in non-AC environments.	Explicitly accounts for occupant expectation and "dwell time." Prioritizes Thermal Preference over fixed PMV in transient zones.	High-traffic airport concourses or glass-fronted lobbies with high solar gain and intermittent occupancy.
GB 50736	No	No explicit transient clause, but uses Category I & II classifications for different temperature ranges.	Category I: high comfort (24 °C–26 °C); Category II: wider tolerance/energy saving (26 °C–28 °C).	Comfort zones are based on sedentary states; Category II is effectively used as the "transient standard" for large halls.	Airport terminals are often designed to Category II to accommodate walking passengers with higher met rates.

- Short occupant dwell time, as reflected in spatial organization and amenities
- Thermal contrast or transition between zones
- Reduced or absent occupant control (i.e., limited ability to adjust environmental conditions through behavioural means such as opening windows, adjusting thermostats, and/or modifying clothing)
- Partial or indirect conditioning
- Spatial function as connectors (corridors, vestibules, atria, etc.)

These definitions are nuanced and context-dependent, but they consistently highlight the limitations of applying standard comfort models without adaptation.

On the basis of this review, and supported by the classification framework shown in Fig. 1, this paper proposes the following working definition: indoor transient spaces are spatial zones within buildings characterized by reduced or absent occupants' access to environmental control, combined with: (a) designed for short dwell time — configured for limited-duration occupancy as part of a single visit rather than sustained use [16,28], and/or (b) transitional spatial function — serving principally to connect or mediate between thermally or functionally distinct zones [1,7,16]. Table 2 further elaborates on the definition with qualifying and disqualifying factors for these spaces that fall outside the scope of spaces that traditional thermal comfort models serve, and require distinct consideration in both design and regulation.

Occupant dwell time should be interpreted as a typical design characteristic rather than a strict threshold, recognizing that some transient spaces (e.g. airport terminals or hospital waiting areas) accommodate extended stays while retaining a transitional spatial function.

Question 2: What is the importance of addressing thermal comfort in transient spaces?

The importance of addressing thermal comfort in transient spaces can be understood through three interconnected dimensions: their consequences for occupant health and wellbeing, their impact on building energy performance, and their role in shaping occupant impressions of a facility.

Transient spaces accommodate a wide range of occupant activities, facilitating circulation and wayfinding in transport hubs, serving as waiting areas in hospitals and hotels, enabling informal social interaction in atria, and offering sheltered environments for physical and social activities. Despite relatively short occupancy durations, thermal conditions in these spaces carry measurable consequences for wellbeing. Thermal discomfort in transient spaces has been shown to induce physiological stress responses, including elevated heart rate variability and altered skin temperature, even below the threshold of conscious discomfort [29–32]. This is particularly significant for vulnerable populations: elderly occupants, patients in hospital waiting areas, and young children in care or education facilities are disproportionately exposed in precisely the spaces most likely to be classified as transient, and face heightened risk from poorly conditioned thermal environments. A poorly conditioned hospital waiting room during a heatwave, for instance, can exacerbate physiological vulnerability in patients who are already under stress [33]. Transient spaces can equally serve as thermal buffers that moderate the effects of extreme outdoor conditions, actively protecting occupants during weather extremes, a benefit that is lost when these spaces are under-designed or over-conditioned [10,34,35]. The mechanisms through which thermal conditions shape these outcomes at the level of perception and pleasure, including alliesthesia and the positive effects of controlled thermal excursions, are explored in detail in Question 7.

The implications for building energy performance are equally significant and insufficiently recognized. The large scale and physical permeability of many transient spaces, entrance doors, atrium glazing, and indoor-outdoor interfaces that facilitate frequent occupant movement and air exchange, make their thermal environments inherently difficult to stabilize, resulting in energy consumption that studies show can be up to three times greater than in adjacent non-transient spaces [9,36]. This disproportionate energy burden is compounded by the systematic misapplication of steady-state comfort models to environments they were not designed for – a challenge examined in depth in Question 3. Because transient occupants are less physiologically acclimatized and more tolerant of wider thermal ranges than their non-transient counterparts, the strict comfort zones defined by standard models are poorly suited to these contexts [9,10]. Forcing transient spaces to meet non-transient thermal criteria therefore risks not only misrepresenting occupant experience, but also generating severe energy inefficiency through unnecessary over-conditioning, a point developed further in Questions 3 and 7.

Beyond individual experience, the thermal environment of transient spaces has direct consequences for how occupants perceive the facilities they enter. The lobby, terminal concourse, or building atrium is typically the first and last thermal environment an occupant experiences in a building. Moreover, evidence indicates that these initial impressions carry over into overall assessments of the facility [29]. Thermal discomfort at point of entry negatively affects environmental satisfaction ratings, perceived service quality, and return intent, with implications for hospitality operators, airport authorities, healthcare administrators, and commercial landlords alike. Occupants in transient spaces also form expectations based on the space type: a hotel lobby perceived as uncomfortably hot on arrival shapes the guest's overall experience of the property, while a well-tempered hospital waiting area reduces perceived waiting time and reported anxiety [33]. These facility-level effects represent a compelling business case for appropriate

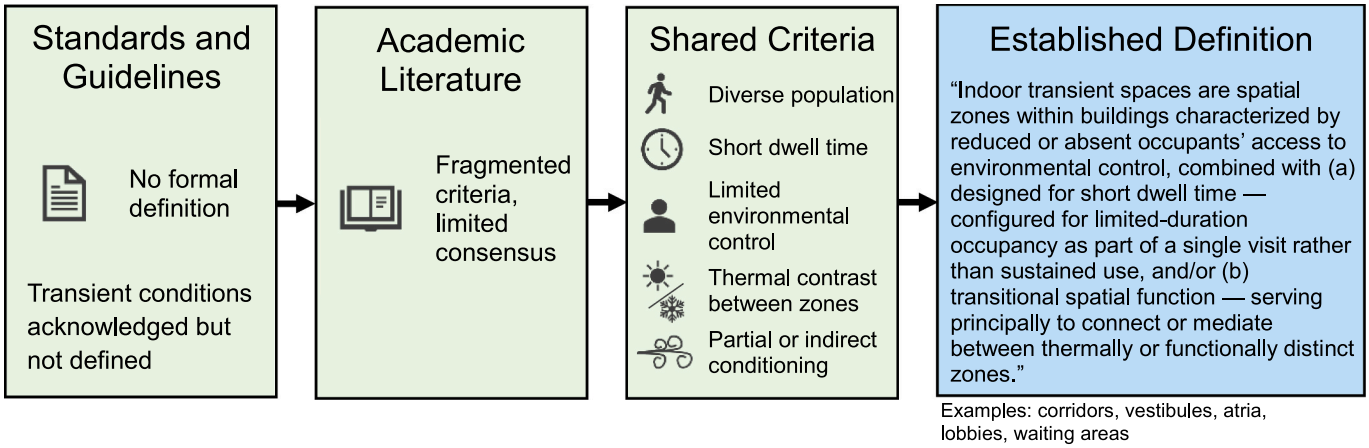


Fig. 1. Conceptual framework for the definition of indoor transient spaces.

Table 2
Criteria for the definition of indoor transient spaces.

Requirement	Criteria	Definition	Qualifying Indicators	Disqualifying Indicators	Examples[†]
Required	Reduced or absent environmental control opportunities for occupants	Occupants have limited or no ability to adjust thermal conditions in the space	Limited or no access to thermostats, operable windows, or other personal thermal controls; conditioning managed centrally or absent	Occupants can independently and meaningfully adjust their thermal environment (e.g. thermostats, operable windows, HVAC controls)	corridors, vestibules, atria, lobbies, and waiting areas
Either or both	A – Designed for short dwell time	The space is configured for occupancy of limited duration as part of a single visit, not for sustained or continuous use, as reflected in its spatial organization, furnishing, and amenities	Limited to no amenities for extended stay; spatial layout oriented toward movement or waiting rather than sustained activity	Space is designed and furnished for continuous, repeated, or sustained occupation (e.g., fixed workstations in offices, or dedicated long-stay seating for classrooms)	waiting areas and transportation terminals
	B - Transitional spatial function	The space serves principally to connect or mediate between thermally or functionally distinct zones, rather than to support primary or prolonged occupation	Primary circulation or passage route; connects spaces of distinct thermal or functional character; occupancy is incidental to movement through the space	Space's primary design purpose is to host sustained activity, not to facilitate movement or passage between other zones	corridors, vestibules, lobbies

[†] The examples provided are illustrative rather than exhaustive, as the classification depends on the intended function, occupancy characteristics and level of environmental control rather than the architectural form alone.

thermal comfort management in transient spaces, one that extends well beyond regulatory compliance.

In sum, and as further detailed in the subsequent sections, addressing thermal comfort in transient spaces requires moving beyond rigid non-transient criteria. By embracing the dynamic nature of these environments, it is possible to simultaneously enhance the psychological and physiological well-being of occupants while preventing over-conditioning, optimizing overall building energy performance, and improving occupant experience and satisfaction.

Question 3: What are the challenges in designing transient spaces that achieve thermal comfort?

Designing transient spaces to achieve thermal comfort presents unique challenges due to the interplay of three key issues, as illustrated in Fig. 2: (1) their (often) distinctive architecture, (2) the unique performance and control requirements of their building systems, particularly HVAC systems, and (3) their dynamic, short-term and highly variable occupancy (in terms of dwell times as well as characteristics such as age, gender and other demographic differences). From a design

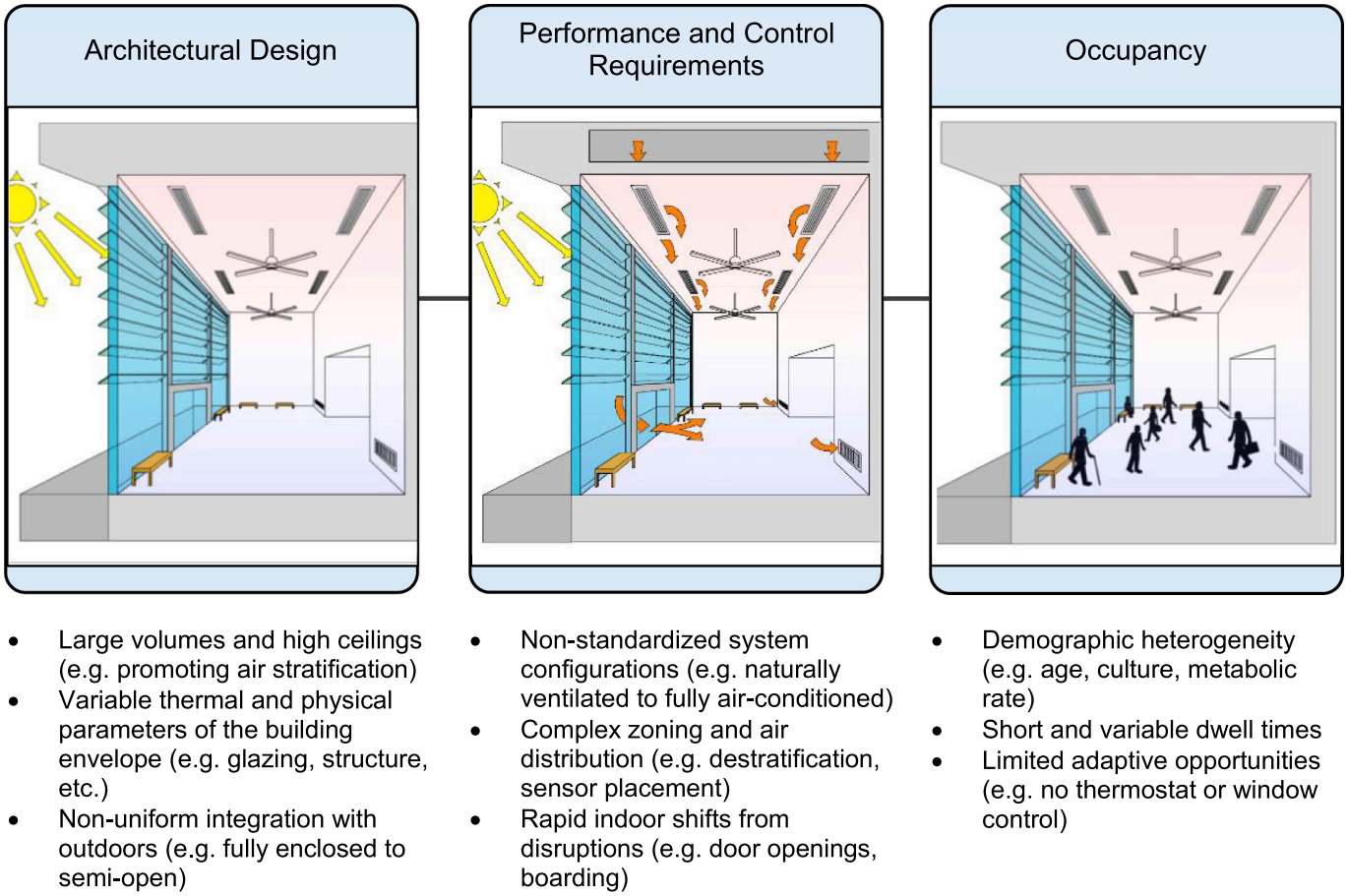


Fig. 2. Characterization of the key challenges in designing transient spaces: (1) distinct architecture, (2) unique performance and control requirements of building systems, and (3) dynamic, short-term and highly variable occupancy.

perspective, these issues create complex and rapidly changing indoor conditions that complicate the delivery of consistent thermal comfort in transient spaces, characterized by short dwell times and fluctuating occupancy.

The architectural challenges of transient spaces stem from their highly distinctive features. These spaces often have large volumes and high ceilings that promote air stratification, as well as varying levels of integration with the outdoors, ranging from fully enclosed to semi-open environments. Their envelopes frequently incorporate extensive glazing or steel-and-glass constructions that typically offer lower insulation and lead to localized discomfort. In addition, their forms and materials follow unique, often futuristic artistic visions, which means there is rarely a repetitive or standardized architectural model for such spaces [1,10,16,17,37]. As a result, these spaces frequently experience rapid shifts in temperature, humidity and radiation [37]. The architectural challenges are also linked to the goal of minimizing energy consumption and emissions and thus the need to implement passive strategies. These solutions (e.g. external shading devices, roof canopies, use of greenery, determining the building's orientation, the division and definition of interior space, etc.) can significantly impact the original design concept, limit the architectural design of the transient space and impose unique challenges and high requirements for HVAC operation and environmental control.

A key difficulty of HVAC design in transient spaces is the lack of clear definitions and dedicated guidelines for transient spaces, as most standards do not explicitly address HVAC design for these environments. Only a few exceptions exist: CIBSE Guide A provides the most specific guidance, offering zone-differentiated criteria for airport terminals that account for activity level and dwell time [20], GB 50736–2012 applies general civil building comfort categories that designers adapt for airport use in the absence of dedicated airport parameters [21]. Transient spaces also exhibit wide variability in system configurations, ranging from naturally ventilated environments to fully air-conditioned systems. The placement of sensors and zoning strategies can therefore be more complex and less standardized, particularly when trying to avoid localized overheating or overcooling [38,39]. Furthermore, transient spaces often contain multiple sub-space functions, such as atria, restaurants, retail areas, circulation zones, and waiting areas, within a single open volume, each with different environmental requirements [40]. Finally, frequent disruptions, such as door openings, passenger boarding, or semi-open passages (in the case of airports), can cause rapid shifts in indoor conditions, further complicating HVAC control and operation [41,42].

The unique nature of occupancy in transient spaces also presents its own set of challenges, as they are characterized by highly variable and unpredictable occupancy patterns [40,43]. Occupants in these contexts differ widely in age, cultural background, activity levels, clothing insulation, body composition, and metabolic rates [44–46]. Critically, these are not only static individual differences but also dynamic within a single visit: an occupant's met and clo can shift markedly over minutes, for instance, as they transition from brisk walking to standing to seated waiting, or add/remove outerwear at entry, rates of change that steady-state comfort inputs are not designed to represent. Additionally, the transient spaces are characterized by the rapid changes in the number of people, from empty to fully crowded areas. Alhamad indicates that highly variable occupancy pattern is a challenge to maintaining thermal comfort conditions and HVAC system due to dynamic fluctuations of the latent and sensible heat gains [47]. Such heterogeneity leads to very diverse thermal expectations, making it difficult to define a universal comfort target [16,45,48–50]. Moreover, occupants typically experience short and irregular exposure times, which undermine the steady-state assumptions commonly used in comfort models [9]. Unlike in offices or homes, users also have very limited adaptive opportunities, as they can rarely control windows, thermostats, or make any other environmental adjustments. Finally, occupants in transient environments are often subject to additional contextual stressors, such as travel anxiety, time pressure, crowding, and sensory overload, which can further influence or amplify perceptions of thermal discomfort.

These architectural, system-level, and occupancy-related issues create a highly dynamic and uncertain indoor environment that challenges conventional approaches to thermal comfort design in transient spaces. Their strong interdependence means that decisions on building form, HVAC configurations, and occupant interactions cannot be considered in isolation. As a result, designing transient spaces requires more integrated and adaptive strategies capable of responding to their unique and rapidly changing environmental conditions, as well as their heterogeneous user needs. Understanding how occupants actually behave, move, and adapt within these environments is equally critical to informing such strategies, discussed in Question 4.

Question 4: How do occupant behaviours, expectations, and movements in transient spaces vary from non-transient spaces?

Occupants exhibit fundamentally different behavioural patterns in transient spaces compared to non-transient environments such as offices and homes. In familiar settings, everyday behaviours become routine and habitual, either automatic or triggered by environmental cues [51,52]. Review papers from the IEA's EBC Annex 79 [1,2] study occupant behaviour but predominantly focus on space more representative of non-transient environments, such as offices and residential buildings, where behaviour and patterns are more predictable. Transient spaces such as shopping centres, atria, and gyms disrupt the routines and schedules found in those settings. These disruptions arise from varied occupancy patterns, different expectations of the space, and constraints on the adaptive actions available to occupants. Occupancy in transient spaces is more short-lived and involves highly variable populations. For example, workers in an office building rarely change in composition, whereas shoppers in a mall or travellers in an airport are more variable over shorter timeframes. This variability in occupant composition produces a wider range of individual preferences, social backgrounds, and physical characteristics, all of which shape how occupants perceive and respond to the thermal environment.

Psychologically, occupant behaviour can be described as either intentional or habitual [52,53], both driven by a goal, e.g. maintaining thermal comfort. Familiar environments like homes and offices provide repetitive cues that guide occupants toward established routines. Conversely, unfamiliar environments like transient spaces demand more active attention, as there is no established routine and environmental control is limited. Within thermally uncomfortable transient spaces, occupants tend to rely on adaptive strategies such as adjustments of clothing, relocation to a different environment, or simply acceptance of discomfort in service of their primary purpose (e.g., visiting someone, shopping, or catching a flight) [16]. This reliance on adaptive strategies and shifts in expectations creates a moving target for thermal comfort evaluation, as occupants are more likely to underreport dissatisfaction relative to the percentage predicted by PMV-PPD-based models [16]. It is worth noting, however, that not all adaptive strategies are available in these contexts. Research shows that visual discomfort can take precedence over thermal discomfort, with occupants preferring a thermally uncomfortable space over one with distracting daylight glare [16]. This underscores that adaptive behaviour in transient spaces is shaped not only by thermal stimuli but by competing environmental and social priorities.

Some behaviours in transient spaces are habitual rather than reactive. Several studies show that occupants tend to occupy familiar spots out of habit, e.g. taking the same seat in a coffee shop or atrium, even when this choice conflicts with thermal comfort, typically for social or routine reasons [16,54,55]. Activity levels are also more variable in transient spaces than in non-transient counterparts, which tend toward less metabolically demanding activities such as desk work or seated dining. The transitional function and short dwell times of transient spaces imply that occupants rarely remain sedentary and change tasks frequently, e.g. walking through a mall and stopping at stores to shop or browse, and then sitting at the food court to have a brief meal [16,56].

Importantly, occupants re-evaluate their thermal sensation over time, introducing a temporal dimension that standard snapshot-based evaluations do not capture [57]. Together, these factors, including dwell time, metabolic rate, psychosocial influences, and adaptive behaviours, form a complex and interdependent set of variables that must be considered in any robust thermal comfort evaluation for transient spaces.

Expectations also shape the types of behaviour performed within a space. Travellers at airports who planned and completed online check-in engage in more diverse activities such as eating and shopping compared to those who did not [58]. Many transient spaces are prone to inducing anxiety in occupants, given large crowds, high volumes of movement, or both [59]. Crowded environments such as indoor mall walkways, train stations concourses, and airport terminals induce anxiety through faster pacing and higher crowd density [60,61]. In situations of anticipatory anxiety stress, humans show an increase in internal body temperature, producing a thermally uncomfortable state [62]. While stress also occurs in workplaces and homes, the predictability and familiarity of those environments gives occupants greater capacity to manage it. Prior planning can partially mitigate discomfort, such as checking a train concourse map before departure to feel familiar with the layout, for instance, but cannot fully suppress the physiological responses to crowded and fast-paced environments.

Understanding occupant thought processes and decision-making in transient spaces remains a core challenge: data and frameworks are sparse compared to research on permanent spaces. This is due to the challenges faced in gathering behavioural data in transient spaces, being considerably more difficult than in non-transient environments. These measurement challenges are examined in detail in Question 5.

Question 5: What challenges do we face in measuring and monitoring thermal comfort in transient spaces?

Measuring and monitoring thermal comfort in transient spaces is constrained by the dynamic nature of both the environment and its occupants. While sensors can be used to evaluate microclimate variability, this practice requires significant upfront investment and lacks a standardized methodology. A constantly changing occupant profile further complicates the implementation of standard thermal comfort surveys and limits the effectiveness of both subjective data collection and physiological measurement.

Various methods exist for surveying occupants [63], and longitudinal studies (i.e. measuring the same occupants periodically over several days) are among the most common in thermal comfort research. However, longitudinal studies are rarely feasible in transient spaces, as they depend on recurring occupancy. Evidence suggests that the high mobility and short dwell times of transient occupants force survey timing and location to be opportunistic [64], relying on chance encounters contingent on the occupant's location, available dwell time, and willingness to participate. Physiological measurement faces analogous constraints: wearable sensors cannot be deployed on sporadic populations in the way continuous monitoring permits in non-transient settings. Calculating thermal mass, heat flux, and thermal equilibrium, which are standard approaches in non-transient studies, becomes exceedingly complex when both the occupancy and the indoor environment are simultaneously dynamic, with multiple rapidly changing variables interacting with one another. Additionally, occupants in transient spaces lack the sense of ownership over the environment that they hold at home or at work, which reduces their motivation to employ adaptive strategies and cause them to endure thermal discomfort rather than act on it. This behavioural limitation undermines the validity of dissatisfaction-based comfort metrics. Modern computing, however, offers promising avenues to address some of these constraints. Online data-mining, drawing on social media posts or review websites, provides insight into the types of adaptive behaviours occupants use, their perceived comfort levels, and their expectations of the space [65,66]. Frameworks built on social sensing data can be used in conjunction with agent-based simulation using machine learning or large language models to generate synthetic data, improving understanding of how behaviour differs between transient and non-transient spaces.

Limitations in surveying also challenge the alignment of subjective and objective measurements, particularly for the microclimates experienced by individual occupants. Capturing microclimate variability at the necessary resolution requires high-granularity data, which in turn demands a more developed sensor network than is typically used in conventional indoor thermal comfort studies [2]. This level of investment enables the assessment of environmental conditions across different areas and conditions within a transient space. A further complicating factor is the sensitivity of the indoor thermal environment to seasonal changes [67–69], which necessitates all-season data collection to determine appropriate year-round indoor conditions.

Several studies adapt available methods and technologies to address these challenges. However, seamlessly incorporating these solutions into future research requires standardized methodologies: scalable and replicable survey tools, and environmental monitoring strategies designed to improve the comparability of findings across studies. A standardized and holistic approach to thermal comfort evaluation in transient spaces, one that accounts for the risks and limitations specific to these environments, would enable results to be meaningfully compared across studies and contexts. Three major factors currently impede the measuring and monitoring of thermal comfort in transient spaces and necessitate further exploration: (1) capturing microclimate variability at sufficient spatial and temporal resolution; (2) capturing the physiological effects of short dwell times and varying activity levels on occupants; and (3) accounting for diverse occupant clothing, behaviour, dwell times, and adaptive strategies. Addressing these measurement challenges is a prerequisite for the development of more reliable and contextually appropriate comfort models- a challenge discussed in Question 6.

Question 6: What is the suitability of existing thermal comfort models for transient conditions?

Widely adopted thermal comfort models have been developed under steady-state assumptions and are limited in their ability to address the unsteady, heterogeneous, and dynamic characteristics of transient spaces. The two most commonly applied frameworks, the PMV-PPD model and the adaptive comfort model, differ fundamentally in their approach but share the same core limitation: neither is designed to handle the rapid environmental changes, short occupant dwell times, and diverse behavioural patterns that define transient environments. Understanding where these models succeed and where they fail in transient conditions is essential for identifying the most promising directions for model development.

The PMV-PPD model [70] predicts thermal sensation based on human heat balance, assuming steady-state conditions with negligible heat storage. The adaptive comfort model [71] is empirical and based on behavioural adaptation to prevailing outdoor conditions, and does not address time-varying thermal exposure at all. In transient and dynamic conditions, such as step-changes in temperature or thermal ramps, thermal overshooting becomes prominent: occupants experience a thermal sensation that temporarily overshoots the new steady-state level before settling, a phenomenon neither model captures. Similar to the standards reviewed in Question 1, the modelling literature specifically refers time-varying thermal exposure (ramps, step-changes, cycling temperatures) as “transient conditions”, which is distinct from but related to the broader concept of transient spaces as defined in this paper. The two senses of the term converge in transient spaces, where both the environment and the occupancy are simultaneously dynamic.

Beyond PMV-PPD and the adaptive model, a range of thermal sensation models apply to the indoor temperature conditions found in buildings. Per the review by Koelblen et al. [72], dynamic thermal comfort can be predicted by limited number of models like the DTS model by Fiala [73], the TS model by Zhang [15,74], the TSV model by Takada [75], and Kingma's model [76]. A separate category of models, thermoregulation models such as JOS-3 [77], simulate the physiological heat exchange processes underlying sensation without directly

outputting a thermal sensation vote, and serve as the computational foundation for several of the sensation models listed above. The performance of these models under both steady and time-varying conditions is assessed by Koelblen et al. [78], showing that accuracy is highest for steady exposure (below 1.0 thermal sensation unit) and lowest for ramp exposures (up to 1.6 units). Among the models evaluated, Fiala's Dynamic Thermal Sensation (DTS) model outperforms the others under dynamic conditions. More recently, Vellei [79] introduces the DMV (Dynamic Mean Vote) model, a modified version of DTS that incorporates skin wettedness, high metabolic rates such as those encountered in exercise, and thermal overshoot in skin temperature during dynamic changes. The DMV model outperforms the DTS model by 10–15%.

Despite this progress, existing models including the DMV model, focus on predicting mean thermal sensation and lack personalization. They also address whole-body sensation almost exclusively, with limited attention to local thermal discomfort—sensations arising from draft, radiant asymmetry, vertical air temperature differences, or contact with warm or cold floor surfaces—despite the fact that standards such as ASHRAE 55 and ISO 7730 already specify local discomfort criteria for steady-state environments [18,19]. In transient spaces, where occupants frequently stand or move near glazed façades, floor-level air supply diffusers, or door thresholds, local discomfort dominate the overall thermal experience, yet no equivalent local discomfort criteria exist for transient conditions. The commonly used models listed above therefore struggle to forecast the thermal sensation of individuals in real environments that are simultaneously transient and spatially non-uniform [72]. This challenge is compounded by the rapid fluctuations in met and clo that characterize transient occupancy as identified in Question 3. These shifts further interact with the mood or activity type of the occupant (e.g. the urgency of transit versus the leisure of browsing). Individual and population-level differences, particularly age, but also sex, body composition, and health status, further shape thermal response and have been highlighted in recent studies as an increasingly important axis for optimizing comfort outcomes [44–46]. A personalized approach to thermal sensation and comfort prediction is thus essential. Furthermore, dynamic thermal sensation models are computationally complex and rely on detailed human thermoregulation modelling, limiting their practicality for widespread deployment in real-world monitoring and control systems. Simpler data-driven models represent a viable alternative, but require individual-level data collection to be effective, a constraint that directly intersects with the measurement challenges identified in Question 5. Developing models that are both physiologically grounded and practically deployable in transient environments represents one of the most critical open challenges in the field. Crucially, the same characteristics that make these spaces difficult to model — short dwell times, variable thermal exposure, and occupant movement — also present distinct design opportunities that go beyond the neutrality paradigm, explored in Question 7.

Question 7: What are the opportunities in designing transient spaces related to thermal comfort?

The majority of the literature on thermal comfort in transient spaces focuses on the avoidance of negative thermal experiences- keeping conditions within accepted comfort zones to prevent dissatisfaction [80,81]. However, a growing body of research challenges this neutrality paradigm, pointing to the benefits of more dynamic thermal conditions that temporarily exceed conventional comfort boundaries [29,81–84]. A key insight underlying this shift is that the very characteristics that make transient spaces difficult to design (i.e. short dwell times, occupant movement, variable thermal exposure, and limited environmental control) also afford designers considerably more flexibility than non-transient environments permit. Because occupants do not remain long enough to fully acclimatize, strict thermal neutrality is neither necessary, nor always desirable. This question addresses the opportunities that arise when transient spaces are designed not merely to minimize discomfort, but to leverage their inherently dynamic thermal character as a positive resource to expand the range of design choices available.

These opportunities can be grouped into measures for: a) leveraging transient spaces as buffer zones to minimize thermal shock when moving between indoor and outdoor environments; b) eliciting occupants' alliesthesia to enhance thermal comfort and overall user experience; c) adding health-promoting encouragements through controlled thermal excursions; and d) reducing operational energy demand and improving the building's energy performance (addressed in Question 2).

The first opportunity concerns the role of transient spaces as thermal buffers. Indoor-outdoor temperature differences can be substantial, exceeding 40 °C in a Canadian winter, for example, requiring significant adjustments in clothing and physiological state. Where transient spaces are designed as intermediate thermal zones between the outdoor climate and fully conditioned interior spaces, the transition can be distributed across multiple smaller thermal steps rather than experienced as a single abrupt change. This allows occupants more gradual behavioural adaptation, such as removing or adding clothing layers, and more progressive physiological adjustment, reducing acute thermal stress and the perception of discomfort on arrival. From a design flexibility standpoint, this approach permits a wider range of architectural configurations, including semi-open, naturally ventilated, or partially conditioned spaces, that would be thermally unsuitable as primary occupancy spaces but are entirely appropriate as staged transition zones. Evidence supports the effectiveness of this approach: studies of indoor-to-outdoor transitional zones demonstrate that carefully staged temperature gradients significantly improve occupant thermal acceptability compared to direct transitions [85,86].

The second opportunity relates to alliesthesia, the phenomenon whereby the perceived pleasantness of a thermal stimulus depends on the occupant's internal thermal state [87]. When an occupant feels warm, a cooler stimulus is perceived as more pleasant than a neutral one; conversely, warmth is experienced as pleasurable when one is cold. This physiological mechanism, originally described by Cabanac [87], and subsequently confirmed in built environment research across temporal, spatial, and seasonal contexts [32,88–90], offers a distinct design opportunity in transient spaces. Because occupants arrive from thermally distinct prior environments and move through briefly, the conditions that elicit alliesthesia are already naturally present. Designing with this in mind, for instance, allowing a slightly cooler lobby to heighten the pleasantness of entering a warm interior, or a warmer transitional zone to make a cooled office feel more refreshing, means transient spaces need not deliver thermal neutrality. Instead, they can be designed to produce intentional, pleasurable thermal contrasts that enhance the overall experience of the building. Critically, this also expands architectural design freedom: spaces that would be considered thermally suboptimal under steady-state criteria (e.g., highly glazed atria, exposed steel structures, semi-outdoor environments) become valid and even desirable, when thermal variability is a design intention rather than a failure. This is supported by evidence that acceptable thermal ranges in transient spaces are broader than in non-transient environments: Avantaggiato et al. [91] report that acceptable upper limits in shopping mall transitional spaces extend to 27.5 °C under humid subtropical conditions, notably higher than the typical steady-state upper limit of around 26 °C, confirming that occupants tolerate wider ranges in these contexts [10,92,93].

The body of evidence suggesting that excursions outside the comfort zone have health benefits is still small but growing. One example is the study by Hanssen et al. [83], which demonstrates positive effects of cold exposures on insulin sensitivity of patients with type 2 diabetes mellitus. Pallubinsky et al. [84] also report positive effects of thermal conditions outside the comfort zone on humans' metabolic profile. While these mechanisms and findings require further repetition and proof, they confirm the potential already discussed alongside alliesthesia of designing transient spaces in a way that they offer opportunities for short-term exposures outside the comfort zone.

Given the potential to elicit pleasure and create positive health

effects through transient spaces designed for dynamic exposures partly outside thermal comfort zones, a key challenge that remains is the question of acceptability. To what degree, and under which circumstances, occupants accept or even welcome conditions that are not conventionally comfortable, and what role information about potential health benefits might play in shaping those perceptions, remains scarcely researched. At the same time, this paradigm carries significant potential for energy savings, carbon reduction, and the downsizing of HVAC capacity, as developed in Question 2.

Taken together, these opportunities suggest a fundamental reframing of the design objective for transient spaces. Rather than treating them as imperfect approximations of non-transient comfort environments, spaces that must meet the same thermal criteria as offices or classrooms but inevitably fall short, they can be understood as spaces with their own distinct comfort logic, uniquely positioned to deliver thermal variety, physiological stimulation, and energy efficiency simultaneously. This reframing carries direct implications for design freedom: architects and engineers working on transient spaces are not constrained to the narrow thermal targets that govern non-transient environments, but can instead work with a broader palette of environmental conditions, architectural forms, and systems configurations. Spaces with high glazing ratios, semi-open boundaries, or variable conditioning, configurations that would be thermally problematic in non-transient contexts, become viable, and even advantageous, when the dynamic thermal character of the space is understood as a feature rather than a deficiency. This paradigm also carries significant implications for HVAC sizing and energy performance, as spaces designed for intentional thermal dynamism rather than strict uniformity offer meaningful potential for reducing conditioning loads, downsizing installed capacity, and lowering operational costs. Realizing this potential, through adaptive envelope design, optimized air distribution, and occupant-centric ventilation management, requires the building technologies examined in Question 8.

Question 8: What is the role of building technologies in improving thermal comfort in transient spaces?

The physical parameters that govern users' thermal comfort (e.g., air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation) are well established in the literature [18,19]; however, understanding how these factors interact in transient spaces and the role that building technologies can play remains complex. This complexity primarily arises from the diverse ways that users interact with and within these spaces, as well as from the heterogeneous nature of transient environments themselves. For instance, while the technologies employed to condition a waiting room share similarities with those used in residential heating and cooling systems, the HVAC solutions required for large-scale transient environments, such as atria, airports, or shopping malls, differ significantly. There is a set of boundary and design conditions that play a role in the variability of technologies, technical feasibility, and the perception of comfort. The

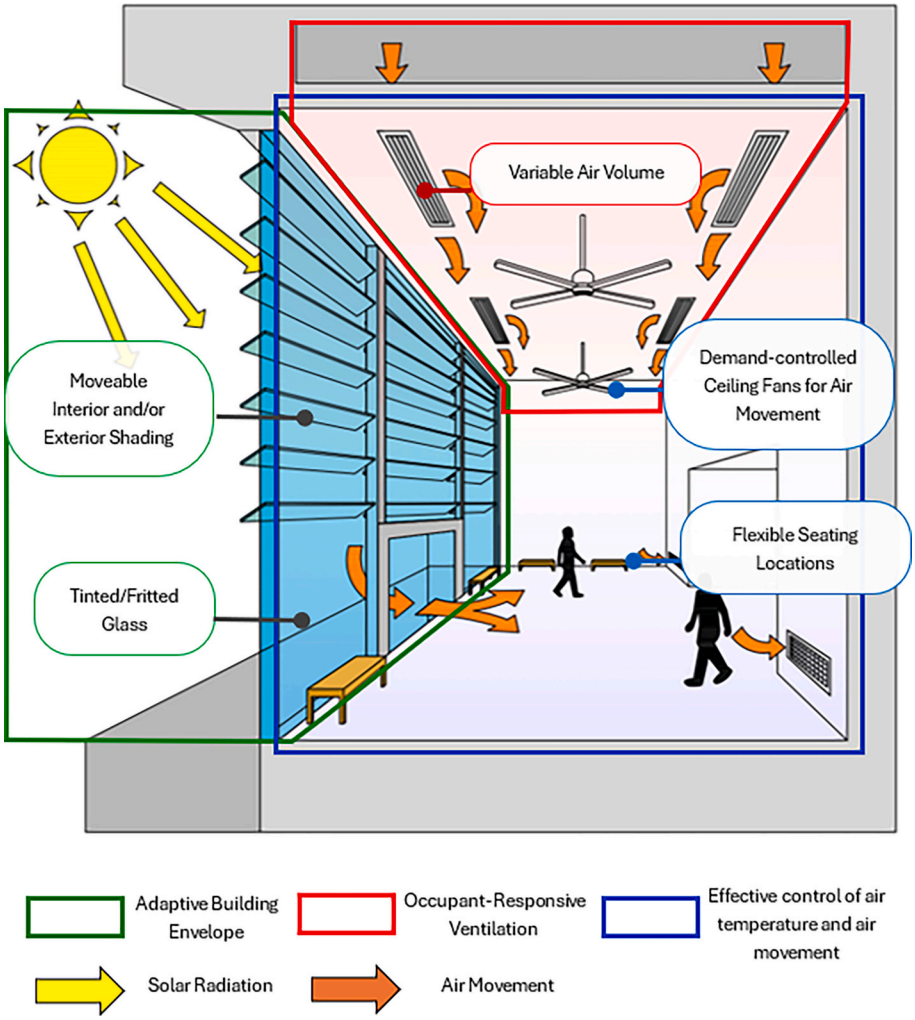


Fig. 3. Schematic cross-section of a representative large transient space illustrating three technological frontiers governing thermal comfort: (1) adaptive envelope, (2) air temperature distribution and air movement control, and (3) occupant-centric ventilation management. Cool-to-warm grading indicates vertical thermal stratification.

main ones are window-to-wall ratios, occupancy number and duration, metabolic activity levels, space height and total volume (and related air stratification effects), shading, infiltration and air exchange rates (especially due to frequent door openings), control zoning strategies, interaction and/or integration with other space HVAC systems (e.g., in shopping malls), connection with the outdoor space, and other elements that impact internal loads and users' perception. Fig. 3 illustrates the intrinsic technological frontiers involved in the built environment of a lobby.

In large transient spaces, the building envelope is a significant determinant of the thermal environment, mediating solar radiation and surface temperatures that influence mean radiant temperature (MRT). In these large transient spaces, particularly those with extensive glazing, radiant effects are frequently the dominant source of discomfort, with the significance of envelope performance depending on occupants' proximity to the façade and the extent of available adaptive opportunities such as shading or repositioning [1,3]. Field studies in airport terminals in Lhasa, Xi'an, and Nanjing observed differences of 3–5 °C between black globe and air temperature attributable to large glazed façades [48,49], with vertical thermal stratification reaching up to 2–3 °C per vertical metre in large public spaces [86,94]. Adaptive envelope technologies, such as double-skin façades, low-emissivity coatings, and especially dynamic shading, can mitigate radiant asymmetry while preserving the visual openness that characterizes large transient spaces. In particular, shading design and control strategies reduce radiant temperature asymmetry and limit operative temperature extremes in highly glazed zones, thereby improving local comfort conditions [95]. However, because shading directly affects both solar heat gains and daylight availability, its operation entails an inherent thermal-visual comfort trade-off that is especially critical in glazed atria and terminal halls [96].

The control of air temperature distribution and air movement represents the second technological frontier. Due to large volumes and variable occupancy, transient spaces exhibit pronounced vertical temperature gradients and non-uniform air velocity distributions. Air and heating and cooling distribution systems, such as displacement ventilation, underfloor air distribution, and radiant floor heating, have been tested to address these gradients with varying effectiveness depending on space geometry and occupancy patterns. In high-altitude terminals such as Lhasa, radiant floors combined with passive solar gain prove effective in maintaining acceptable comfort despite thin air and intense radiation [94]. Meanwhile, studies in summer transient spaces suggest that optimal air temperatures between 25 °C and 28 °C minimize thermal stress when moving from outdoor heat to cooled interiors [86]. Air movement itself has ambivalent effects: moderate speeds (0.2–0.4 m/s) enhance comfort and freshness perception, while higher values have a positive or negative impact depending on the indoor temperature and thermal sensation of the users [97]. Ceiling fans are particularly effective, as they allow localized and adjustable air movement that occupants can perceive as refreshing without necessarily increasing overall air speed beyond comfortable thresholds. Field investigations in underground malls and airport halls demonstrate that controlled airflow direction and velocity can increase thermal acceptability by up to 80% [50]. Thus, advanced control strategies that dynamically regulate air speed and direction, linking such systems to occupancy sensing, can leverage airflow as a comfort resource rather than a disturbance.

The third technological dimension concerns airflow and thermal load management as a means of responding to occupant-driven heat gains. Transient spaces accommodate fluctuating crowd densities that generate highly variable internal heat gains, making static set-points poorly suited to maintaining comfort. Variable Air Volume (VAV) systems are particularly well-suited to these conditions, as they dynamically adjust airflow rates in response to changing thermal loads across different zones, preventing both under- and over-conditioning without the energy penalty of constant-volume operation. When coupled with multi-zone strategies and predictive algorithms, VAV systems can further adapt to the rapid occupancy shifts characteristic of transient environments. The shift toward occupant-centric and model predictive control (MPC) frameworks illustrates the direction of this evolution. Li et al. [98] demonstrate a passenger-centric MPC framework in Guangzhou Baiyun Airport, integrating occupancy-based fuzzy set-point resets and causal neural network prediction. This system reduces energy consumption by up to 46% while maintaining thermal comfort and indoor air quality, exploiting free cooling when conditions allow. Such approaches exemplify how digital technologies can reconcile comfort performance with sustainability goals in large transient environments.

Overall, building technologies act as both physical and cyber-physical mediators between the unstable external environment and the human body. By combining adaptive envelopes, smart air distribution, and intelligent ventilation control, transient spaces can deliver acceptable comfort across diverse conditions and occupancy patterns. The emerging direction is not to impose thermal uniformity but to embrace variability, designing systems that learn from occupant behaviour, anticipate transitions, and adapt in real time. In this sense, the role of technology in transient spaces extends beyond control: it enables a dynamic equilibrium between environmental responsiveness, energy efficiency, and human adaptability. Leveraging these technologies to systematically balance occupant experience, energy efficiency, and resilience across diverse transient space types is one of the challenges addressed in Question 9.

Question 9: What is needed to optimize thermal comfort in transient spaces?

Optimizing thermal comfort in transient spaces requires a multifaceted approach that reflects their inherently dynamic nature and varied occupant responses. The reframing that optimization in transient spaces is not the pursuit of strict thermal neutrality but the balancing of occupant experience, energy efficiency, and resilience has been established in Questions 2 and 7. This section addresses the operational pathways through which that balance is achieved: advanced microclimate monitoring, adaptive control systems, occupant-centric design, and passive architectural interventions, each playing a distinct and interconnected role.

Advanced microclimate monitoring is a prerequisite for effective optimization. High-resolution sensing is necessary to capture rapid variation in temperature, humidity, and air velocity across the spatial and temporal gradients characteristic of transient environments [99]. To achieve this without disrupting occupant movement, non-intrusive and distributed monitoring methods are essential [100,101]. The data produced by such systems forms the foundation for adaptive control, and directly addresses the measurement gaps identified in Question 5.

Fixed HVAC setpoints are not ideal for the rapid and irregular fluctuations characteristic of transient spaces and often struggle to balance energy efficiency with variable loads. Predictive control strategies such as model predictive control and deep reinforcement learning (DRL) enable co-optimization of energy, indoor air quality, and thermal comfort [102]. Digital twin frameworks integrating BIM, IoT, and machine learning allow real-time simulation and zone-specific responses, enabling systems to adjust before comfort limits are breached [103,104]. These approaches are especially valuable in transient spaces because they can anticipate occupancy-driven thermal loads rather than simply reacting to them, a capability that steady-state models, as discussed in Question 6, cannot provide.

Occupant-centric factors must also be incorporated into the optimization process, accounting for thermal history, expectations, and adaptive behaviours (e.g., adjusting clothing, altering activity levels, etc.) that influence metabolic rate and perceived comfort. The broader thermal tolerance of transient occupants, and the design potential of alliesthesia established in Question 7, can be operationalized directly: thermal transitions that would register as discomfort under neutrality-based criteria can be designed to produce positive sensory experiences when the sequence and magnitude of thermal change is carefully managed [11,105]. Additionally, to reduce the thermal discomfort in

such heterogeneous group in transient spaces as established in Question 3, especially with regard to different age groups and high variable occupancy, Personal Comfort Systems (PCS) can be implemented. Such devices, located in dedicated zones of the transient space, equipped with individual regulation/thermostats, can provide effectively local heating, cooling or/and ventilation. These include heated/cooled chairs, mechanical fans, etc. [106–108].

Architectural and passive interventions further support optimization by moderating conditions before mechanical systems engage. Strategies such as sequential thermal zoning, radiant systems, shading, and vegetation can foster gradual adaptation and thermal delight [109]. In areas with multiple indoor-outdoor interfaces, moderated mixing of environments is preferable to abrupt thermal shifts, creating a buffer that eases the physiological transition for entrants [110].

The specific purpose and spatial function of a transient space must also shape its optimization targets. Corridors designed purely for circulation require different thermal strategies than waiting areas, semi-outdoor atria, or healthcare lobbies. Field studies confirm that the specific activity and dwell time shape the thermal response of occupants [11,86]. Grouping spaces by function and expected behavioural adaptation therefore provides a more coherent framework for defining transient comfort targets than applying a universal building standard uniformly. This also directly informs the function-specific criteria and design guidelines that the field currently lacks [111].

In sum, optimizing thermal comfort in transient spaces demands clearly defined, function-specific comfort criteria tailored to transient occupancy; control strategies capable of responding to rapidly changing conditions; and comfort evaluation frameworks that incorporate short-term human adaptation and multisensory perception [11]. While AI and machine learning-based comfort models offer significant potential, their complexity and implementation challenges suggest that robust, non-learning heuristic models often provide a more reliable and practical solution for scalable deployment at this time [112]. The interdisciplinary dimensions of these optimization opportunities, spanning physiology, data science, architecture, and urban planning, are explored in Question 10.

Question 10: What interdisciplinary opportunities exist in research on thermal comfort in transient spaces?

Thermal comfort in transient spaces presents unique challenges arising from fluctuating, difficult-to-control environmental conditions, diverse occupant behaviours, and varying spatial functions. Addressing these complexities requires dedicated interdisciplinary collaboration across human physiology, behavioural science, data science, architecture and urban planning, psychology, and sociology. This cross-disciplinary integration enables the development of adaptive, occupant-centric solutions that foster environmental sustainability, energy efficiency, and holistic comfort.

On human adaptation and transient perception, recent studies have quantified how rapid thermal transitions (e.g., moving from outdoors to indoors) affect the human body. Research shows that occupants in transitional waiting areas adapt via clothing adjustments, repositioning or relocating, or using personal devices (e.g., handheld fans). Field investigations in Italian shopping centres demonstrate that users adapt to a broader range of thermal conditions than conventional models predict, indicating that transient spaces can achieve substantial energy savings while maintaining high comfort levels through more flexible, adaptive design and control strategies [91]. Gnecco et al. [113] use wearable sensors to reveal that short-term exposures can induce physiological stress even without conscious discomfort, identifying physiological patterns associated with individual acclimation time that deepen understanding of how occupants experience transient spaces at the individual level.

The interdisciplinary contribution of data science is equally significant. Pisello et al. [114] develop monitoring procedures for HVAC commissioning integrated with IoT sensor data from transient spaces in multi-functional buildings, demonstrating that human-centric zoning strategies reduce energy use by 18% while maintaining comfort. Sleiman and Ouf [40] review the wide interdisciplinarity between thermal comfort, control engineering, and operational management for energy saving in airport terminals, environments where dynamic occupancy, indoor-outdoor interactions, and strict performance requirements make them ideal case studies. Their review finds that demand-controlled ventilation (DCV) excels in airports, adjusting ventilation rates by real-time occupancy for savings of up to 60%.

These findings also carry architectural and urban planning implications. Jiang et al. [115] analyse the effectiveness of transitional buffer zones, such as vestibules with greenery, in stabilizing microclimates near building entrances. Larger-scale studies of urban resilience in public transit hubs in heat-vulnerable cities examine the strategic effect of integrating shade structures and reflective materials to mitigate extreme temperatures. Quadros et al. [116] assess the reliability of microclimate models for investigating intra-urban canyon thermal comfort, providing strategic analysis for designing human comfort in semi-open spaces in dense urban layouts. These studies collectively demonstrate how transient space research connects building-scale thermal comfort to urban-scale climate resilience. This emphasizes the multi-domain opportunity that warrants dedicated future investigation, including the integration of outdoor thermal comfort metrics, urban heat island modelling, and building energy simulation into unified frameworks.

Thermal comfort research in transient spaces faces significant methodological challenges that require interdisciplinary solutions. Data integration is complicated by the diversity of available sources, including qualitative surveys, crowdsourced data [117], and sensor-based measurements, which resist unified analysis. The deployment of physiological sensing is further constrained by the structural realities of transient environments identified in Question 5 (i.e., the lack of recurring occupancy, short dwell times, and reliance on chance encounters), make continuous monitoring logistically infeasible at scale, meaning that developing appropriate measurement methods for these spaces is in itself a cross-disciplinary challenge requiring collaboration between human physiology, sensor engineering, and behavioural science. Ethical concerns also arise around balancing occupant privacy with the extensive data collection enabled by IoT technologies, compounded in transient spaces by the anonymous and temporary nature of occupancy. Despite these obstacles, strategic opportunities exist: AI-driven digital twins offer the potential to integrate microclimate data with urban-scale climate models, enabling better design of transient spaces and more accurate prediction of comfort during extreme weather events.

Looking ahead, future research should prioritize cross-disciplinary metrics capable of capturing the full complexity of transient comfort experiences. A Transient Comfort Index that integrates physiological, behavioural, and environmental variables from a multidomain [118] and multisensory perspective [119], as proposed in Fig. 4, would provide a unified framework for assessing both individual and collective dimensions of comfort, including the capacity to cope with environmental stressors in indoor-outdoor transient environments. Multi-domain approaches that bridge thermal, acoustic, visual, and air quality dimensions of comfort represent a particularly promising direction, as the interactions between these modalities are likely to be more pronounced in transient spaces, where occupants have less control and less time to adapt, than in non-transient environments. Establishing a shared language and measurement structure for transient indoor spaces is an essential step toward integrating them into broader comfort evaluation protocols, regulations, and performance-based design practices.

A critical open question for the proposed Transient Comfort Index (TCI) is how the relative weighting of individual comfort parameters should differ from that adopted in steady-state models, particularly because occupants of transitional spaces generally lack the degree of environmental control assumed by conventional comfort frameworks. Local air velocity provides a representative example. In steady-state models, air movement is often considered primarily in relation to draft

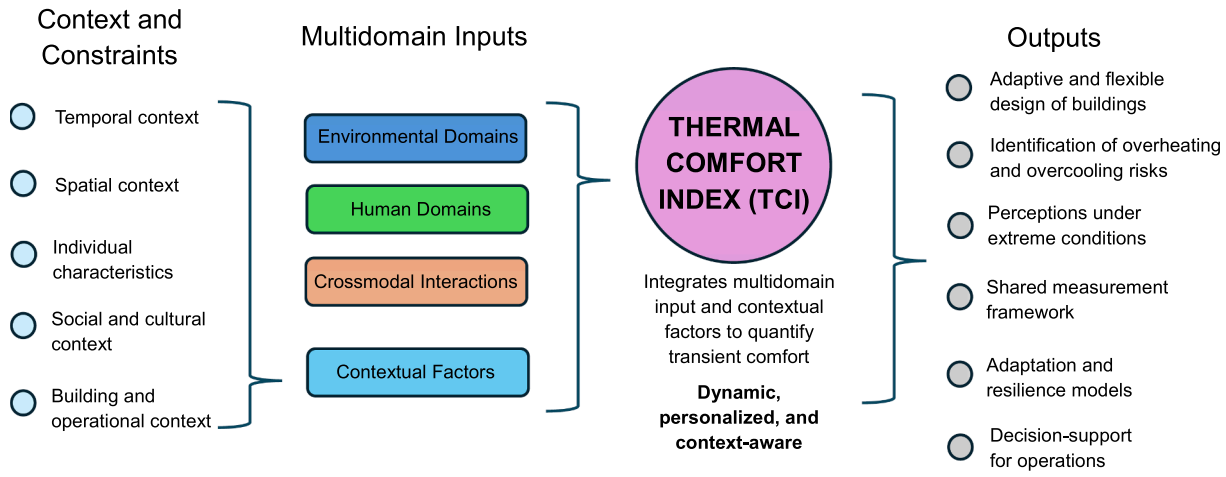


Fig. 4. Conceptual framework for proposed Transient Comfort Index.

risk and therefore as a potential source of discomfort. In transitional spaces, however, moderate airflow (e.g., 0.2–0.4 m/s) instead enhance perceived freshness and thermal relief and even generate pleasurable sensations during indoor–outdoor transitions through alliesthesia, as discussed in Question 7 and in relation to ceiling-fan performance in Question 8. In naturally ventilated outdoor and semi-outdoor environments, airflow also result from urban advection, which represents a key mechanism for mitigating outdoor overheating. Indeed, the capacity to capture and promote natural airflow is one reason why transitional architectural typologies such as porticoes, cloisters, arcades and shaded passageways have historically provided attractive and thermally valuable intermediate environments across different climates. These considerations suggest that air velocity should be treated as a context-dependent and potentially bidirectional contributor to comfort, rather than as a fixed parameter or, more restrictively, a predetermined penalty. Its weighting depend on prior thermal exposure, the direction and magnitude of the environmental transition, metabolic activity, clothing and individual characteristics. At the same time, potentially adverse effects, including excessive convective cooling or dehydration under particular combinations of temperature, airflow and activity, should not be overlooked. Such interactions further illustrate the complexity of defining universal weighting factors in transitional spaces, which are inherently less controlled than conventional indoor environments.

Radiant temperature asymmetry poses a related challenge. Steady-state approaches generally assume relatively stable exposure to surrounding surfaces, whereas occupants moving through transitional environments experience brief but substantial changes in radiant conditions, for example when passing between shaded areas and highly irradiated glazed or opaque surfaces (Question 8). Such responses be more consistent with the rate-sensitive thermoreceptor mechanisms discussed in Question 6 than with conventional duration- or time-averaged exposure metrics. A transient-specific index therefore need to account not only for the instantaneous magnitude of radiant asymmetry, but also for its direction, temporal variability and rate of change during the transition, together with occupant-related parameters such as metabolic rate, clothing insulation, previous exposure and individual adaptive characteristics. At present, however, to the best of these authors' knowledge, the available literature does not provide sufficient empirical evidence to establish robust quantitative re-weighting functions for either air velocity or radiant asymmetry. A reliable and generalisable formulation of the TCI would require dedicated experimental validation across multiple transitional-space typologies, climatic and seasonal conditions, exposure sequences and durations, and heterogeneous participant populations. The present framework, illustrated in Fig. 4, should therefore be regarded as a conceptual basis, consistent with the multi-domain comfort theoretical formulation [120], rather than a fully calibrated predictive index. Its quantitative formulation and validation represent a particularly promising direction for future research and a potential dedicated development arising from the present work.

3. Conclusion

Transient indoor spaces, such as corridors, lobbies, atria, airport terminals, hospital waiting areas, and other spaces characterized by short occupant dwell times and limited environmental control, occupy a critical but underserved position in the built environment. They function simultaneously as thermal buffers between outdoor and indoor climates, as spaces that shape the first and last thermal impressions of a building, and as environments whose conditioning demands can be up to three times greater than adjacent non-transient spaces. Yet the existing literature has treated them inconsistently, applying steady-state terminology, measurement methods, and comfort models to conditions for which those tools were not designed. This paper addresses that gap through a ten-question synthesis of current knowledge. Its first and most foundational contribution is a working definition: indoor transient spaces are spatial zones within buildings characterized by reduced or absent occupants' access to environmental control combined with: (a) designed for short dwell time — configured for limited-duration occupancy as part of a single visit rather than sustained use, and/or (b) transitional spatial function — serving principally to connect or mediate between thermally or functionally distinct zones.

The synthesis reveals that the challenges of transient spaces are largely structural. Their distinctive architecture, including large volumes, extensive glazing, semi-open boundaries, creates thermal environments that are inherently variable. Their HVAC requirements are more complex and less standardized than those of primary occupancy spaces. The occupancy pattern changes dynamically – from unoccupied to densely occupied conditions. The occupants are heterogeneous, short-staying, and subject to contextual stressors, such as crowding and travel anxiety, that influence thermal perception independently of environmental conditions. And the methods available for measuring and monitoring comfort in these spaces, including surveys, physiological instruments, environmental sensors, are practical in non-transient settings but face major constraints in transient spaces.

At the same time, the paper identifies that these same characteristics create genuine opportunities. Because occupants do not remain long enough to fully acclimatize, strict thermal neutrality is neither necessary nor always desirable. Broader thermal ranges are tolerated and, through the mechanism of alliesthesia, can generate positive thermal experiences. Transient spaces can be designed as staged buffer zones that ease physiological transitions, as environments that promote health through

mild thermal excursions, and as architecturally ambitious forms, having high glazing ratios, semi-outdoor configurations, that could be thermally problematic in long-stay contexts but can be appropriate for transient spaces. This reframing has direct implications for HVAC sizing, energy performance, and design freedom.

Realizing this potential requires progress on several fronts. Comfort models must move beyond mean thermal sensation toward personalized, dynamic prediction frameworks that account for thermal history, short dwell times, and individual variability. Measurement methodologies must be adapted, through non-intrusive sensing, opportunistic survey protocols, and digital twin integration, to capture the microclimate and occupant diversity of these spaces. Control systems must shift from fixed setpoints toward predictive, occupant-centric strategies that co-optimize comfort and energy in real time. The field must also embrace the interdisciplinary scope that transient comfort research demands: spanning human physiology, behavioural science, data science, architecture, and urban planning, and working toward cross-domain metrics such as a Transient Comfort Index that can integrate physiological, behavioural, and environmental variables into a unified evaluation framework.

In terms of definitional and typological work specifically, future research should prioritize the development of robust typological frameworks that align spatial function with thermal criteria, the creation of consensus definitions through expert consultation and comparative studies, and the exploration of how regional, cultural, and climatic contexts affect both the perception and classification of transient zones. Establishing a shared structure and a common language for defining and evaluating transient indoor spaces is an essential step toward integrating them into broader comfort evaluation protocols, performance-based design practices, and, ultimately, the international standards that currently leave them unaddressed. By consolidating a decade of fragmented findings into a single ten-question framework, this paper offers the first structured synthesis of thermal comfort in transient spaces, providing a common reference point from which future definitional, modelling, and design work can proceed.

CRediT authorship contribution statement

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Claude Sonnet 4.6 to improve readability and clarity. After using the tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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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Data availability

No data was used for the research described in the article.

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