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Ten Questions Concerning the Application of Adaptive Thermal Comfort in Mixed-Mode Buildings

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Abstract

The recently completed IEA Annex 69 (*Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings*) identified mixed-mode (MM) building design and operation as key strategies for the buildings sector in its transition towards a low-carbon mode. Mixed-mode is short-hand for naturally ventilated designs with supplemental air-conditioning that can be called upon whenever and wherever external climatic loads and/or internal loads dictate. Success of the MM strategy requires shifting the sector's concept of thermal comfort away from a static comfort zone towards an adaptive approach in which the indoor comfort zone drifts in the same direction as external weather and seasonal trends. The potential for mixed-mode design arises from its applicability in both new construction and existing building stock. The objective of this paper is to elevate awareness of the mixed-mode design concept within the building sector and related research communities. Furthermore, it aspires to influence international thermal comfort standards and guidelines, advocating for a more explicit endorsement of adaptive thermal comfort in mixed-mode applications. Towards this end, we address ten critical questions concerning the application of adaptive thermal comfort in mixed-mode buildings. The questions elucidate the fundamental aspects of MM buildings, the role of adaptive thermal comfort, and the broader implications for building design and operation.

Keywords

thermal comfort; mixed mode; natural ventilation; personal comfort systems; hybrid ventilation; sustainable buildings

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Introduction

Demand for cooling in buildings is projected to triple by 2050, and it is the main driver of spiralling energy demand throughout the buildings sector. It has been described by the International Energy Agency as *"… one of the most critical yet often overlooked energy issues of our time*" (IEA, 2018). This trend is observed in both developing and developed economies. In the developing economies, most of which are located in hot, humid tropics and adjacent subtropical regions, the upward trajectory of cooling demand is driven by rising household incomes, while in industrially advanced economies the main driver is the seemingly inexorable rise in comfort expectations of building occupants (Luo et al., 2016; Hassani et al., 2024).

The impacts of explosive growth in cooling demand are manifold, but the four most consequential are the following:

- Indoor cooling demand for power is met with electricity predominantly generated by fossil fuel combustion, therefore contributing to *greenhouse gas emissions* (GHG) and global warming. Over time, the supply of decarbonised electricity may increase as the use of renewables increases, but national and regional ambitions to move towards more sustainable energy production vary widely.

- Electricity requirements of mass cooling demand induced by heat waves often exceed *grid supply capacity*, forcing load-shedding (brown-outs) or even worse, unplanned power black-outs.

- The waste heat generated by air-conditioning (AC) equipment contributes to the *Urban Heat Island* phenomenon in high-density urban areas, self-reinforcing demand for more cooling indoors.

- Increasing cooling means using more refrigerants. The eventual leakage or intentional release of these harmful substances into the atmosphere can contribute to ozone layer depletion and/or have a high global warming potential, while the presence of PFAS (per- and polyfluoroalkyl substances) in others poses a threat to human health. Increased cooling demand therefore stresses the need to develop and implement less harmful alternatives. Largely, development is driven by legislative bans on conventional refrigerants but should come out as a market advantage to producers.

Proposed abatement strategies for cooling demand are legion, but most attention to date has been focused on capital intensive improvements to the thermal performance of building envelopes, and optimisation of the energy efficiency of new building services and controls. Relatively less attention has been given to the main "consumer" of energy in buildings, namely the building occupant. The recent IEA-EBC Annex 69 (IEA, 2022) highlighted the benefits of climatically relevant indoor thermal comfort setpoints. Commonly referred to as adaptive thermal comfort (Humphreys and Nicol, 1998), this demand-side management approach renders naturally ventilated (NV) design solutions feasible across more diverse climatic regimes for more months of their respective climatological year, compared to the business-as-usual scenario of static comfort set-point temperatures.

Despite the obvious benefits of adaptive comfort in naturally ventilated buildings, engineers may feel uneasy about the diminished level of indoor environmental control in buildings that rely solely on natural ventilation compared to the certainty associated with fully air-conditioned solutions (Brager, 2006). But this is not an either/or proposition and there is a third way, known as mixed-mode, which combines features of naturally ventilated and air-conditioned solutions to maximize comfort benefits. In this paper we aim to amplify the case for the mixed-mode design concept across the buildings sector and allied research communities, and to nudge international thermal comfort standards and guidelines towards a more direct prescription of adaptive thermal comfort in mixed-mode applications. Towards this end, in this paper we address ten common questions and misconceptions, ranging from: definitions of the modes being mixed, the mapping of different comfort models onto ventilation/conditioning modes, the degree of occupant control over the ventilation/conditioning modes, the nexus between mixed-mode and low-energy buildings, mixed-mode control logic, viability of mixed-mode in future climate scenarios, and the applicability of mixed-mode strategies across various building typologies. The questions can be broadly categorised as relating to the application, design and operation of mixed-mode buildings using adaptive thermal comfort (ATC) – Figure 1. The ten questions were chosen based on the literature, authors' experience, and the identification of knowledge gaps and recurring themes in recent publications. The questions address current research trends, offering insights that can inform both future research directions and practical advancements.

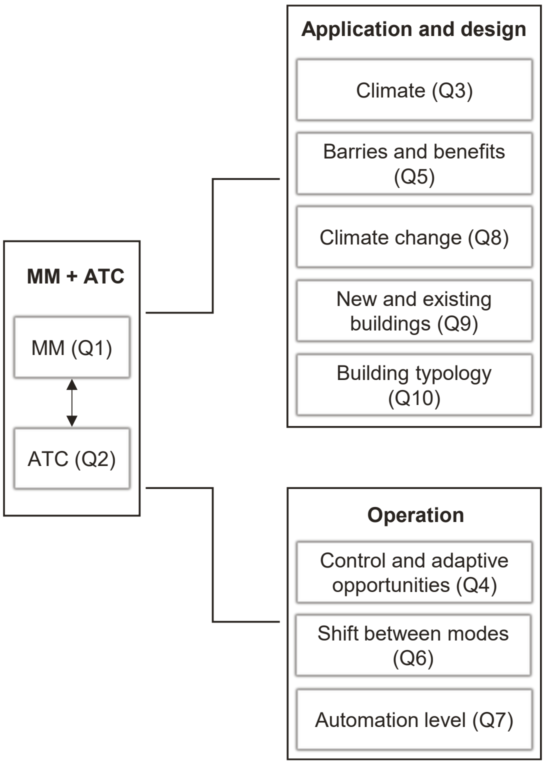

Figure 1. Schematic visualisation of the ten questions.

Ten questions (and answers) concerning the application of adaptive thermal comfort in mixed-mode buildings

1. What is a mixed-mode building?

Mixed-mode refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled) or other passive inlet vents, and mechanical systems that provide air distribution and some form of cooling and/or heating (Brager, 2006). The term 'mixed-mode' is sometimes used interchangeably with 'hybrid ventilation' in the literature. However, while hybrid ventilation is simply the combination of natural and mechanical ventilation, 'mixed-mode' encompasses a broader range of strategies and systems. The extant mixed-mode studies available in the literature were mostly conducted using a combination of natural ventilation and cooling. This indicates the widespread use of the term 'mixed-mode' in contexts involving warm external conditions where supplementary cooling is required. However, this terminology is not commonly used in climates where heating is dominant, despite the fact that, for example, a large proportion of European buildings use heating during the colder seasons and rely on natural ventilation in summer and during transitional periods. While these buildings would technically be classified as 'mixed-mode', they are not usually reported as such in the literature.

It would be a mistake to think of a mixed-mode building as simply a conventional air-conditioned building where the windows open. Mixed-mode buildings are designed to optimize the use of both natural ventilation and mechanical systems, which requires a balance of automated and manually controlled operational strategies that can respond to daily and seasonal weather variations as well as the unique needs of each building. While there is no single universal solution, the intention of a well-designed mixed-mode building is to allow spaces to be naturally ventilated during periods of the day or year when it is feasible or desirable, and uses mechanical cooling (or heating) only as necessary when natural ventilation is not sufficient, to maximize comfort while avoiding the significant energy use and operating costs of year-round air-conditioning (Borgeson and Brager, 2010). To achieve this, a naturally ventilated or mixed-mode building will likely incorporate other climate-responsive strategies as well. Particular attention should be paid to shading and daylighting to reduce cooling loads, as well as thermal mass so that direct ventilative cooling during the day might be combined with nighttime cooling. Even in a climate where mechanical cooling or heating may be needed much of the year, an integrated design solution likely will extend the times of the year when mechanical cooling or heating can be avoided.

Mixed-mode buildings are typically classified in terms of their operation strategies, which describe whether the natural ventilation and mechanical cooling/heating are operating in the same or different spaces, or at the same or different times. Various terms have been used interchangeably in the literature. Illustrated in Figure 2, the simplest ways to describe these are: “zoned” or “spatial” (where mechanical cooling and natural ventilation operate in different areas of the building), “concurrent” (where mechanical cooling and natural ventilation can operate in the same space at the same time), and “change-over” or “temporal” (where the building switches between mechanical cooling and natural ventilation on a seasonal or daily basis).

Before describing these terms in more detail below, it should be noted that there does not seem to be a “standard” mixed-mode approach in practice today – each building continues to be unique. While the practice has been for a building overall to be labeled as mixed-mode, given the diversity of thermal zones and types of controls in a building, perhaps the descriptions below are best applied to spaces rather than simply one label for the entire building. This would then have implications for the thermal comfort criteria used for the various zones during the design and operation phases. It should also be noted that, for many mixed-mode buildings, operating conditions might deviate somewhat from their original design intent (e.g. a building originally designed for seasonal changeover between air conditioning and natural ventilation may, in practice, operate both systems concurrently).

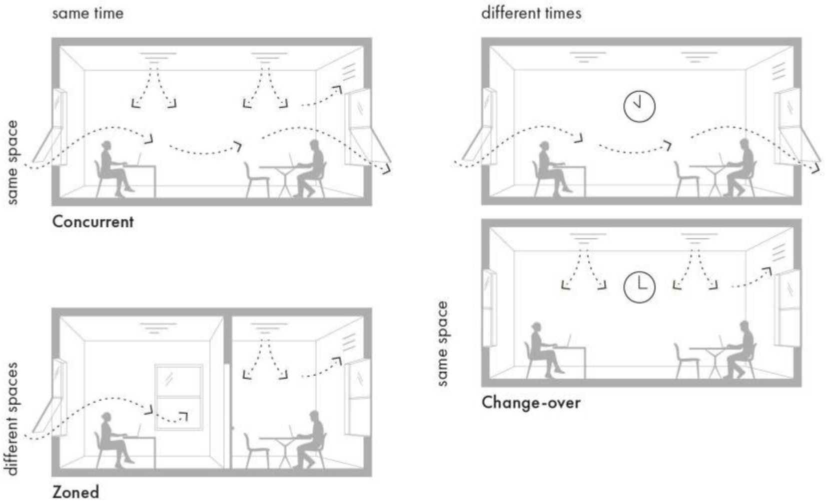

Figure 2. Operation strategies of mixed-mode buildings. Source: DeKay and Brager, 2023.

Zoned/Spatial

This category generally refers to the physical distribution of different conditioning strategies (i.e., different spaces, but same time). The benefits of natural ventilation only penetrate a limited distance into a building from openings to the outside environment. Central stacks or air shafts can expand its spatial extent, but it is often used only as a perimeter conditioning strategy. Zoned/spatial mixed-mode is a good choice for buildings where deep floor plates create large interior zones (e.g. many existing sealed large office buildings), or there are ventilation requirements in parts of the space that cannot be met by natural ventilation (e.g. labs), or there are other programmatic differences that dictate the use of different strategies (e.g. office space vs. meeting space, low offices with noise or security concerns associated with having operable windows, directionally biased sources of scooped ventilation or non-optimal stack location).

Concurrent

This category describes systems that operate in the same space at the same time. For example, an appropriately scaled Heating, Ventilation, and Air-Conditioning (HVAC) system might supplement a natural ventilation system to extend energy savings and occupant comfort into shoulder seasons or to meet code minimum ventilation requirements in winter. In open plan offices, there can be a blurry line between zoned and concurrent spaces, as zones in these spaces are not physically separated. Concurrent systems raise a common fear that operable windows will result in higher energy demands as building operators pay to condition outside air coming in through open windows. But just because the operable windows and mechanical cooling are present in the same space and have the potential to operate at the same time, it doesn't mean that they always do. For example, you can move your setpoints higher such that the building is primarily in passive mode most of the time, and the mechanical cooling only kicks in to control the peaks. Even though you could potentially lose energy if windows are open when the mechanical cooling is on, you may have much longer periods of time when the mechanical cooling isn't running, and those savings overshadow the waste.

Changeover/Temporal

This category is based on classifying the temporal distribution of conditioning strategies in the same space. These buildings can change their strategies over short time periods (as a system that reacts more or less to outside or inside conditions, like humidity, CO_2, etc.), and/or medium time periods (e.g. night ventilation with mechanical ventilation (MV)/AC during the day) and/or long time periods (e.g. buildings with operable windows that are sealed all winter). The type of operating parameters that dictate which timescale(s) of control are appropriate include climate (from seasonal changes to current conditions), building characteristics (e.g. massing and orientation), and site-local climate conditions. The different time scales of changeover/temporal systems hint at the idea that they might be broken out into additional sub-categories based on the driving conditions of each changeover strategy and the type of control strategies used.

However, the time scales of a changeover/temporal mixed-mode building can be varied and often coexist. A night ventilation system that only operates during summer has seasonal and daily adjustments that it can make. A system that always does the theoretically optimal thing (e.g. achieves the theoretically optimal energy savings or occupant satisfaction, or cost savings) would clearly be changing all the time in response to and in anticipation of indoor and outdoor conditions. Consequently, the controls of good systems are likely to span multiple temporal classifications, whether they are entirely manual, or completely automated.

2. What is adaptive thermal comfort and how does it relate to the operation of a mixed-mode building?

The basic tenet of adaptive thermal comfort theory is that building occupants are active participants in a person-environment system (Brager and de Dear, 1998). These principles can be applicable in any building type, and are particularly relevant to mixed-mode buildings that combine both natural ventilation and air-conditioning. Adaptive comfort theory is characterised by multiple feedbacks comprising occupant interactions with indoor climate, which can be classified into three distinct layers of process, including (a) immediate behavioral adjustment of the six factors identified by Fanger (1970) as controlling the body's heat-exchange with its immediate environment (four environmental—air temperature, mean radiant temperature, humidity and air speed— plus two personal factors of clothing insulation and metabolic rate), (b) longer-term physiological acclimatization, particularly to heat, through enhanced efficiency of sweat evaporation, and (c) a psychological level of adaptation or habituation, whereby the occupant's thermal comfort expectations drift towards the level of their recent thermal exposure (Humphreys, 1981). Recent analysis demonstrated that indoor thermal experience is what primarily drives adaptation, thus making it relevant to all building types (Parkinson et al., 2020).

For buildings with operable windows (naturally ventilated or mixed-mode), several independent meta-analyses of the large thermal comfort field study databases (de Dear and Brager, 1998; McCartney and Nicol, 2002; Parkinson et al., 2020) have demonstrated the strong dependence of comfort temperatures on outdoor climate (a proxy for building occupants' recent thermal exposure in buildings where indoor and outdoor conditions are linked). Empirical evidence sourced from climate chamber experiments and field studies indicates that the slower process of acclimatization is not so relevant to thermal adaptation in the relatively moderate conditions found inside buildings. However, adjustments of the building's adaptive opportunities by the occupants, along with shifts in their comfort expectations, exert a much greater influence over thermal satisfaction, and as such, provide the generally accepted explanation for the dependence of indoor comfort temperatures on outdoor temperature in naturally-ventilated and mixed-mode buildings. The most common behavioural interventions include clothing adjustments and local comfort devices such as fans or radiant heaters, but access to operable windows has emerged from several research studies as the crucial factor in explaining the adaptive comfort model (Brager et al., 2004).

Applying these conclusions from adaptive comfort modelling to the mixed-mode concept of this paper, both modes of the building's operation, active and passive, should comply with the indoor temperature prescriptions of an adaptive comfort model. When the building is unable to passively maintain internal conditions within the adaptive comfort zone, it should switch over to the active mode of operation (cooling or heating). In the interests of minimising energy demand and environmental impacts, an actively conditioned mixed-mode building should target set-points in the upper reaches of the adaptive comfort range during the cooling season, and the bottom end of the range during heating season, in order to minimise the indoor-outdoor temperature gradient. This challenges current international thermal comfort standards (e.g. ASHRAE 55 (2023) and EN 16798-1 (2019)) that allow the assessment of the thermal environment using the adaptive thermal comfort model only for naturally ventilated buildings or for periods when active cooling/heating systems are not in operation. However, this condition may be in flux. At the time of this writing, section L3.2 from Informative Appendix L of ASHRAE 55, when referring to both the PMV and adaptive comfort models, notes that active investigation is underway into how the two models apply in mixed-mode buildings. Supporting evidence for our recommendation can also be found in research demonstrating that people adapt to the indoor conditions that they are accustomed to (Parkinson et al., 2020), which suggests that adopting wider temperature ranges even during the active-conditioning mode could be both comfortable and energy-efficient.

3. Which climate zones will be amenable to the mixed-mode design approach?

This is a difficult question to answer generically since the success of a mixed-mode building depends not only on regional climate, but also the microclimate, urban context, envelope characteristics, and internal building loads. Taking all these into account, one then considers wherever the building in question can satisfy the comfort requirements of its occupants while operating in passive, naturally ventilated mode for a significant part of the year. The scale of benefit in MM buildings is proportional to the percentage of occupied time during which the outdoor climate conditions are favourable for the NV mode of operation.

Undoubtedly, providing comfort without relying on air-conditioning is easier for buildings in temperate climates. This is why most exemplary case-studies of MM buildings have been reported in warm temperate climate regions of the planet (Peng et al., 2022; Gomis et al., 2021). Building energy simulation tools enable designers to quantify the potential of natural ventilation using the 'NV hour', the number of hours per year that comply with the comfort standard. In a comprehensive global simulation exercise (Chen et al., 2017) the most favourable conditions for NV comfort were found in the subtropical highland climate (e.g. South-Central Mexico and Southwest China) due to their mild conditions occurring all year round, and the Mediterranean climate zone which is characterised by hot, dry summers and mild, wet winters (e.g. around Mediterranean Sea, California, Western Australia, and Central Chile). In cold climates, such as parts of Scandinavia, Russia and Canada, NV operation appears feasible: however, the duration during which comfort criteria are met is estimated to be about half that of Mediterranean climates (Chen et al., 2017). Regions with hot and humid weather conditions throughout the year (e.g. Southeast Asia and India), as well as regions with polar climates, generally have limited NV potential (Chen et al., 2017; Gokarakonda et al., 2019).

Climatic factors are therefore crucial when deciding a ventilation and conditioning design strategy, and achieving comfort by exclusively relying on passive means is infeasible in locations where the external climatic conditions fall well outside the adaptive comfort limits for much of the year. Under such circumstances a mixed-mode design can improve on the limitations of a pure NV approach for achieving comfort. For example, US based studies (Emmerich, 2006; Wang and Greenberg, 2015) demonstrate that in the severe climates of central US where a pure NV system is unable to adequately meet cooling or heating loads, the MM strategy can be a promising solution. It is also not uncommon to see MM buildings offering potential energy savings without compromising occupant comfort in more extreme and severe external conditions, for example hot climates of UAE (Friess and Rakhshan, 2017) and Lebanon (Daaboul et al., 2018). Corroborating evidence can also be found in field studies; for example, occupants of MM buildings expressing high levels of comfort during hot summer of Seville Spain (Barbadilla-Martín et al., 2017), and Changsha China (Wu et al., 2019), where daily maximum temperatures routinely reach or exceed 40°C. Interestingly the Seville and Changsha studies were conducted in buildings relying on manual 'change-over' without any state-of-the-art control system or climate-responsive design intent being applied. This suggests, with an integrated design strategy, the MM strategy may be possible even in an extreme climate. For instance, in arid climatic conditions such as hot and dry desert-like climates with large diurnal temperature ranges (e.g. Central Australia, Egypt and Saudi Arabia), a significant energy saving is achievable when MM is accompanied with passive and climate-responsive design strategies such as thermal mass, façade shading, operable windows and night-purge ventilation (Ezzeldin and Rees, 2013). In particular, the building envelope plays a critical role as a protective barrier that moderates the impact of external conditions on indoor spaces. Thus, it is important to consider the building envelope characteristics, which can significantly impact the feasibility of MM operation. Even if the climate is favourable, the design and performance of the building envelope play a crucial role in supporting natural ventilation and passive cooling strategies.

As discussed, the successful integration of MM strategies into building design is sensitive to the building envelope and external climate conditions. Additionally, the urban context and microclimate conditions must be accounted for in MM design and operation. Urban areas often experience unique microclimate effects, such as the Urban Heat Island phenomenon, which can influence the cooling effectiveness of natural ventilation. The presence of surrounding buildings, vegetation, and anthropogenic heat generated in the urban context can affect airflow patterns and temperature variations. It is essential to realistically assess potential energy savings and comfort benefits likely accruing from a mixed-mode strategy in the specific context of building design and its climatological environment. In regions with more hostile external conditions, the viability of a mixed-mode strategy will depend heavily on the integration of climate-responsive design principles into the overall design concept.

4. How does the role of control and adaptive opportunity relate to comfort in mixed-mode buildings?

The success of a mixed-mode building in terms of perceived comfort often depends on finding a balance between automated and manual control, considering both the overall needs of groups and individual thermal preferences. Such control can apply to the building's mechanical cooling, personalized comfort systems where applicable (such as ceiling or desktop fans), and the operation of the windows themselves. It is beyond the scope of this paper to discuss the details of a control system, including what environmental attributes should be measured and how. Instead, we are focusing on the occupant-centric aspects unique to a building with operable windows.

Adaptive opportunity refers to a person's ability to exert personal control over elements of the building that will modify the environmental conditions (e.g. windows, blinds, fans, etc.). While this might affect the physical conditions, it can also affect one's perception. Adaptive theory states that when people have control over a stimulus, it modifies their subjective perception of those conditions. When applied to buildings with operable windows, the adaptive comfort model has shown that people prefer a wider range of temperatures compared to sealed buildings that rely on centrally controlled air conditioning.

Yet, it's not enough to simply be in a building with operable windows; the ability to directly control those windows is essential to the relationship between adaptive opportunity and perceived comfort. A study by Brager, Paliaga and de Dear (2004) in a building with operable windows found that occupants with different degrees of personal control had significantly diverse thermal responses, even when they experienced the same thermal environments and clothing and activity levels. People with higher degrees of control not only had much higher ratings of satisfaction, but their ideal comfort temperatures were much closer to the temperatures they actually experienced. This provides direct support for the adaptive comfort hypothesis that thermal preferences are based not just on conventional heat balance factors, but a shifting of expectations resulting from higher degrees of control over one's environment. The study reinforced the critical idea that buildings be designed so that occupants can be active participants in the indoor climate feedback loop, not simply passive recipients of whatever thermal conditions the building management system delivers.

There are control implications for each of the operating strategies described in Question 1, related to whether the windows and vents are automated vs. manual, where one establishes the thermostat setpoints to determine when the mechanical heating or cooling will turn on, whether there are manual override controls for the HVAC system, or personalized comfort systems available. These options range across timescales measured in minutes, days, and months.

It is important to note that there is no consensus in the industry on the appropriate mix of personal vs. centralized, and manual vs. automated controls. Every building is unique, and the final decisions need to address, in part, different priorities when assessing the tradeoffs involved in optimizing both comfort and energy consumption. Question 7 goes into more detail about automated control strategies. In order to maximize the adaptive comfort benefits of operable windows in mixed-mode buildings, here are some general guidelines about where automated vs. manual windows might work best, and for what functions.

- Automated windows are best used in high spaces, where they are difficult for occupants to reach (e.g. stack, atrium, or clerestory windows, or roof vents), or in public spaces, where they would not be "owned" by anyone and therefore might not be operated manually. They are also most commonly used to meet minimum ventilation requirements, to provide nighttime ventilation, to control overall ambient conditions in the buildings, or to provide controlled ventilation during periods of high winds or rain.

- Manually operated windows are best placed lower in the occupied zone, where they can easily be accessed by the occupants. While there may be a need for some automated windows for the reasons noted above, one should give occupants as much direct control as possible over at least some of the windows to garner the benefits of adaptive comfort.

- In addition to providing occupants with direct control over their thermal environment, manually operated windows are also important for their "psychological benefits", and for providing occupants with a sense of connection to the outdoor environment. For manually operated windows, it's essential that the user controls be visible and readily accessible, placed more closely to the point of need, intuitively obvious and easy to understand, and easy to operate by both occupants and management.

5. What are the main barriers and benefits of mixed-mode strategies?

Compared to conventional full-time AC buildings, mixed-mode is a novel concept in many parts of the world. The delivery of MM buildings is thus challenging without a design team willing to explore innovative approaches that fall beyond industry norms. However, the building sector tends to be inherently cautious, often prioritizing proven design strategies and building services due to concerns about risk and client expectations. Commercial office tenancy agreements often mandate a narrow indoor temperature requirement all year round (typically

22.5±1°C in Australia) (Roussac et al., 2011), and practitioners are compelled to adhere to this stringent operational target even though it falls outside the prescriptions of international comfort standards (e.g. ASHRAE 55 (2023), ISO 7730 (2005) and EN 16798-1 (2019)). Many facilities managers tend to regard the mixed-mode concept as impractical, and such conservative perspectives often prevail in practice (Mongkolsawat et al., 2012). Close collaboration between the client and design team sharing an appetite for innovation and challenging conventional practices are essential prerequisites to the successful implementation of mixed-mode design strategies.

Successful design and operation of mixed-mode buildings requires a comprehensive understanding of all the elements impacting building performance, including envelope and HVAC systems, weather and seasonal dynamics, occupant comfort expectations and behaviours, and their associated energy demands. Despite the complex nature of the MM concept, there is a paucity of comprehensive guidelines for designers and engineers to implement on their projects.

Many building performance rating schemes include assessment criteria that are premised on the presence of air-conditioning, or at least encourage its use (Thomas and Thomas, 2010; Rasheed et al., 2017). It can be challenging for practitioners to implement the integrated approaches required for successful MM strategies in the absence of design assistance and guideline resources. There is a pressing need for guidelines incorporating various MM design and operation strategies tailored for specific climate contexts, building typologies, and occupancy patterns.

Notwithstanding these barriers, mixed-mode buildings deliver many benefits over their conventional AC counterparts, and these can be summarised as follows:

- Occupant satisfaction: In the Post-occupancy Evaluation (PoE) literature it is well documented that occupant satisfaction is higher in MM buildings especially with its indoor thermal environment and air quality, when compared against conventional AC buildings (Brager and Baker, 2009; Kim and de Dear, 2021). Such a high level of occupant satisfaction is often attributed to having a sense of personal control and connection to outdoor environments in the MM context (Ackerly and Brager, 2013). Satisfied workers in a variety of contexts are known to be more productive (Leaman and Bordass, 2001), giving a compelling argument for implementing the MM strategy.

- Relaxed comfort zone: A meta-analysis (Kim and de Dear, 2021) reports that the thermal comfort zone of MM building occupants is wider than that of those in full-time AC buildings. It is believed that adaptive opportunities afforded in MM settings widen the comfort zone of building occupants. The wider the comfort zone, the greater the potential of reducing energy consumed on regulating indoor thermal conditions.

- Health: The ability to introduce outdoor air directly through operable windows in MM contexts is regarded as an effective mitigation measure to potential airborne transmission of infectious diseases such as COVID-19 (Aviv et al., 2021; Park et al., 2021). The MM approach can be a good design solution in response to the raised public awareness of ventilation and air quality in buildings. It is also shown occupants in MM or NV buildings tend to report fewer Sick Building Syndrome (SBS) or Building Related Illness (BRI) symptoms than those in sealed AC buildings (Rijal et al., 2009).

- Energy: It is well documented that a MM strategy can lead to significant energy savings (Salcido et al., 2016). Although the magnitude of benefit can vary a lot between climates, the MM strategy poses significant energy saving potential, ranging from 10~90% relative to buildings with full-time mechanical systems (Kim and de Dear, 2021).

To foster MM implementation, client education appears to be critical, particularly in reframing rigid thermal comfort expectations by referencing the adaptive comfort standards. Early and inclusive collaboration among stakeholders, such as the client, architect, services engineer and facilities manager, can foster a shared understanding and obviate resistance. Demonstration projects and post-occupancy evaluations can build confidence by showcasing successful MM applications. Finally, equipping facilities managers with targeted training can address concerns about complexity and operational reliability, making MM systems more viable in practice.

6. How does a MM building transition between its two modes of operation?

MM buildings comprise a range of different operation setups. Some buildings shift automatically or manually between operation modes while others apply NV and AC concurrently, e.g. in the whole building, or they may use different modes in different zones with varying loads (Brager et al., 2007). Automatic changeover may be performed through a Building Management System with inputs from outdoor and indoor environmental sensors, or manually by allowing the occupants to decide when and where the various modes should be selected.

The aim of shifting from AC to NV operation mode in a MM building is to meet comfort demands and save energy when conditions allow. Shifts from daytime NV to AC should occur when the outdoor conditions no longer support a comfortable indoor environment (Hu and Karawa, 2014). Shifts between operation modes may not be trivial, as the opportunities of using NV will depend on the building's construction materials (exposed thermal mass), window area ratio, façade orientation, and the current internal and external heat loads. Pre-cooling of the building structure at night may further reduce cooling energy consumption and peak demand (Hu and Karawa, 2014). Across buildings, it may therefore not be feasible to specify a single, optimal setpoint for the outdoor temperature, where either NV or AC will be optimal.

Shifts between different operation modes occur most often in temperate climates, where outdoor conditions may make it advantageous to frequently shift between the NV or AC modes after days or weeks. Most existing knowledge on MM operation mode therefore focuses on temperate climates (Peng et al., 2022). In contrast, consistently high outdoor air temperature or humidity, or outdoor air pollution will favour prolonged AC operation.

Modern buildings become more and more complex, often with several interacting mechanical systems, a wealth of sensors, and advanced controls. Future (and some current) MM buildings may better utilize weather forecasts, energy pricing schemes, and simplified building models to foresee optimal operation modes during the coming hours or days (Hu and Karawa, 2014). Such smart buildings may be seen as members of a smart grid energy system, rather than a stand-alone energy consumer. Resiliency may thus be higher in smart MM buildings where scheduled load shifting can be foreseen and accommodated. An element of the European Energy Performance of Buildings Directive, the Smart Readiness Indicator (SRI) was introduced to raise awareness of the benefits of smart building technologies (D-G Energy, 2024). SRI considers building components, such as building automation and electronic monitoring of building systems including dynamic building envelope, ventilation, heating, and lighting, among other systems. In a European context, SRI may thus benefit the expansion of MM buildings.

7. What is the appropriate level of automation in a mixed-mode building's controls and how much of a role should occupants play in the building's operations?

In principle, there is no limit to the potential extent of automation in buildings. This applies to both MM buildings and buildings in general. Modern IoT sensor and control technology allow regulation of the indoor environment to be entirely automated, potentially (but undesirably) excluding the occupants from carrying out adjustment of the system settings. In their comprehensive literature review of hybrid system controls, Peng et al. (2022) identified as many as 42 different parameters related to the indoor environment, outdoor climate, building and installations, as well as occupancy, that were being sensed and used in building controls. Indoor air temperature, relative humidity, and CO_2-concentration were the most prevalent. It is clear that occupants can perceive temperature discomfort that may get stronger over time, even with constant exposure. This will affect their temperature preference and eventually may trigger a behavioural response to reduce the discomfort. However, humans have no receptors for air humidity and adapt quickly (minutes) to air quality when people are the main source of pollution as indicated by the CO_2-concentration. Thus, not all parameters that are routinely used in automated building controls are appropriate for manual occupant control. A high level of building intelligence and automation could potentially optimize building energy performance and reduce the gap between predicted and actual performance (Hellwig et al., 2020). However, allowing the control system to overrule the occupants is not recommended, as several studies have documented that the users' satisfaction with the indoor environment increases with increasing control opportunities (Leaman and Bordass, 1993; Toftum, 2010). For example, Toftum (2010) found that around 90% of the 561 surveyed occupants in 15 mechanically ventilated buildings located in Denmark perceived they had no, or only slight control over their indoor environment, compared to around 60% in naturally ventilated buildings (9 NV buildings, 273 occupants). Despite larger fluctuations of the indoor temperature, the occupants in the NV buildings perceived a higher degree of control and were more satisfied with the indoor environment overall.

The counterpoint to full building automation is personal environmental control, which can be provided when systems allow occupants to condition their individual micro-environment to their preferences (Hellwig et al., 2020). In recent years, the development of personal comfort models has attracted considerable attention from researchers as a potential means to go beyond existing population-average prediction models (e.g. Kim et al., 2018; André et al., 2020; Tartarini et al., 2022). Personal comfort models are typically data-driven and trained on large sets of observed occupant behavioural data using machine learning to predict individual thermal preferences. The models may be used to control personal environmental control systems, but then a dilemma arises if the users of the systems feel they are excluded from the control loop and thus overruled by the system.

In MM buildings running in NV mode, windows or other fenestrations are operated by the users based on their personal preferences. Operable windows may provide a higher level of perceived control than is possible in AC mode, which typically receives input to the controls from a centrally located thermostat. However, regardless of the control mode, systems that are shared by multiple occupants, e.g. as in open-plan offices, are challenging because they cannot simultaneously meet the individual preferences of each and every occupant. Overall, a balance between automation and individual adaptive opportunity is therefore important for optimal building performance and occupant satisfaction in both MM and other types of building, although the optimal level is difficult to generalise.

8. What are the implications of climate change for adaptive comfort in mixed-mode buildings?

Climate change has emerged as the single greatest challenge to humanity in the 21st century. The pace of change has accelerated with clearly noticeable impacts including more intense weather extremes such as heatwaves, droughts, hurricanes, and floods. Global temperatures have risen to record levels (at the time of writing 2024 was being tipped to be the warmest in recorded history) and are confidently predicted to continue on their upward trajectory despite international commitments such as the 2016 Paris Climate Accord aimed at limiting global warming above the pre-industrial global average to just 1.5 °C. The buildings and construction sectors are major emitters of greenhouse gases into the atmosphere and as such must play a significant role in adaptation and mitigation strategies.

During their operational phase, conventional AC buildings can generate positive feedback loops with negative outcomes (i.e., vicious cycles): a) overall, AC consumes energy, which generates carbon emissions, which increase the outdoor temperature, which requires even more energy in AC, and so on, and b) at urban areas, AC usage increases anthropogenic heat emission, increasing heat island effects, which requires even more AC usage, and so on (Jay et al., 2021; Yuan et al., 2022). Furthermore, while outdoor temperatures are on the rise due to climate change, indoor temperatures in AC buildings remain locked in a rather low range (e.g. 22.5 ± 1.5 °C), causing overcooling (Kim and de Dear, 2021; Parkinson et al., 2021). The disconnect with outdoor climate in AC buildings is exacerbated in a warming climate. Despite the obvious impact on energy demand, extensive reliance on AC to keep indoor temperatures tightly controlled impairs the occupants' adaptability to temperature fluctuations and carries significant implications for our health (Pallubinsky et al., 2023). There is mounting empirical evidence in the literature that our energy intensive approach to the maintenance of static indoor environments should give way to more dynamic environments with wider ranges of indoor temperatures (Rupp et al., 2015; Pallubinsky et al., 2023).

To date, the main justifications for allowing greater indoor temperature fluctuations were couched in terms of the adaptive thermal comfort models in international standards (e.g. ASHRAE 55 (2023), EN 16798-1 (2019)), and energy and carbon abatement, but emerging evidence is shifting the arguments towards stimulation of our physiological and psychological adaptive responses. This is crucial to improve our thermoregulatory capacities, thermal resilience, metabolic and cardiovascular health, which all become increasingly essential as global warming progresses (e.g. Pallubinsky et al., 2023).

The imperative to design indoor spaces more closely connected with the climatic context of buildings aligns perfectly with the mixed-mode approach to building conditioning, improving our resilience to climate change. In mixed-mode buildings operating according to the adaptive comfort theory, occupants would be used to both fluctuating temperatures and higher indoor temperatures as the outdoor temperatures rise. For example, Sydney's mid-century climate may more closely resemble that of Brisbane's climate of the 2020s. Therefore Sydney's 2050 adaptive comfort range for indoors should drift towards those currently specified for Brisbane's climate. By gradually nudging indoor temperatures over time, building occupants will be better adapted to future climatic realities. Obviously, however, the upper limits of acceptability of an adaptive thermal comfort model cannot be pushed beyond human heat tolerance thresholds (Sherwood and Huber, 2010; Asseng et al., 2021; Vanos et al. 2023) and should rather be limited within the adaptive comfort range appropriate to the prevailing climate. For instance, overheating in a building in London is not the same as overheating in a building in Singapore or India. A recent adaptive thermal comfort model for naturally ventilated and mixed-mode residential buildings in India (Rawal et al., 2022) suggested an indoor temperature range of 16.3-35.0 ºC, applicable to a 30-day outdoor running mean temperature of 5.5–33.0 ºC, which would be unacceptable in other countries, or could even impose serious health risks to certain populations at present-time. Existing adaptive thermal comfort models will need to be revised (e.g. Parkinson et al., 2020) on an ongoing basis as regional and local temperatures rise, and new local or regional adaptive models will need to be developed and assimilated into international standards.

In the future, one of the main concerns regarding mixed-mode buildings is the impact of climate change on the potential usability of natural ventilation. Depending on the scenario for global emissions and the climate response to the anthropogenic forcing, natural ventilation will continue to be a relevant option to a greater or lesser extent in most parts of the world, e.g. in Canada and the United States (Gilani and O'Brien, 2021), in Australia (Bamdad et al., 2022), in Europe (Bienvenido-Huertas et al., 2023), in Brazil (Sánchez-García et al., 2024; Veloso and Souza, 2024). For instance, reducing carbon emissions according to SSP1-2.6 scenario (Shared Socio-Economic Pathways, according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change-IPCC) will likely keep natural ventilation potential and stabilize demand for AC cooling in office buildings across Brazil by 2050 and 2080 (Veloso and Souza, 2024).

It is likely that many naturally ventilated buildings will need to employ active cooling during weather extremes and certain periods of the year as global temperatures increase. A recurring theme in this 10 Questions paper is that natural ventilation strategies will need to be combined with other passive and/or low-energy design solutions in order to effectively minimize reliance on active cooling. The implications of climate change must be considered when retrofitting existing or designing new mixed-mode buildings (Bamdad et al., 2022). Mixed-mode strategies can reduce the reliance on AC in warmer climates, and undermine the default to fully air-conditioned buildings in colder climates (Heiselberg, 2002). Mixed-mode strategies have been repeatedly highlighted as the most effective approach for the buildings sector to respond to anthropogenic climate change, according to a study that simulated office buildings across the US considering future climate scenarios and various mitigation measures (Wang et al., 2017). Combining natural ventilation with mechanical ventilation (i.e. passive and active ventilative cooling) has also the potential to increase resilience under extreme heatwaves that are typically associated with electricity grid outages (Zhang et al., 2021).

9. Is adaptive comfort in mixed-mode buildings only viable in new construction?

Much of our older building stock, particularly in the residential sector, is already operating with mixed-mode insofar as air conditioning equipment was retrofitted onto a naturally ventilated existing building. In most cases, the operable windows in such buildings are retained after the AC installation, and the building is switched between its AC and natural ventilation modes through purposive occupant behaviour or building automation. The main drivers for the mode changes are in-the-moment, or anticipated, thermal discomfort on the one hand, and conscious energy-related considerations by the occupant on the other (Kim et al., 2017; de Dear et al., 2018).

Having said that, a new building that has been designed to be operated under a mixed-mode strategy following adaptive comfort criteria will generally perform better than a retrofitted building (Brager, 2006), since the latter may often have fundamental design limitations, e.g. preclusion of cross-ventilation capability. Notwithstanding such constraints, it is feasible to retrofit operable windows to an AC building, even those with curtain wall construction, in the same way as it is possible to retrofit AC to a naturally ventilated building with operable windows (Liddament et al., 2006; Brager and Ackerly, 2010; O’Donnavan and O'Sullivan, 2018).

In short, adaptive comfort in mixed-mode buildings is viable in both new construction and existing building stock.

10. Is adaptive comfort in mixed-mode buildings more relevant for certain typologies?

Occupants in their own homes have the most freedom to adapt to their indoor thermal environment i.e. have more adaptive opportunities, than in any other building typology. However, adaptive comfort is a viable option in any building type.

To date, the most widely used adaptive thermal comfort models were derived mainly from datasets comprising office building field studies (de Dear and Brager, 1998; Nicol and Humphreys, 2002) and are included in international standards ASHRAE 55 (2023) and EN 16798-1 (2019) for the simple reason that the overwhelming majority of comfort field study data has come from that building typology (Földváry Ličina et al., 2018). Despite these origins, however, such adaptive models have been used to evaluate thermal comfort for various building types. Since the number of adaptive opportunities for occupants to use, and the comfort restorative potential of each of them, depends on contextual factors such as climate, building type, occupancy and spatial characteristics, it is expected that the range of acceptable indoor temperatures, would also vary according to building type (de Dear et al., 2018). Currently, there is no global adaptive thermal comfort model for non-office building types, yet local or regional adaptive comfort models have been developed for mixed-mode residential buildings (e.g. de Dear et al., 2018; Rawal et al., 2022).

The adaptive thermal comfort model from ASHRAE 55 establishes a band of indoor temperatures for 80% acceptability of 7 K that stretches between 17.4 and 31.7ºC, depending on outdoor climatic conditions. For single-family houses, a wider range for 80% acceptability of 11 ºC was proposed for Australian buildings based on residential field data from humid subtropical Sydney and Brisbane, partly resulting from greater degrees of freedom in clothing choices in the home compared to the office workplace (Jeong et al., 2022). The acceptable zones were 14.6-26.2ºC in Sydney and 16.3-27.2ºC in Brisbane, which is explained by Brisbane's warmer climate (Jeong et al., 2022). For diverse types of residential buildings in India, an 80% acceptability range similar to that prescribed in the ASHRAE 55 adaptive model was suggested (i.e. 7.2ºC), but the acceptable zone was significantly wider, i.e. 16.3 – 35.0ºC (Rawal et al., 2022) – occupants adjusted both clothing and indoor air speeds according to the thermal conditions they experienced.

An analysis of field study data across India showed that the acceptable indoor temperature zone was narrower in offices than in university buildings (Kumar, 2022). The air temperatures and air speeds in offices were lower than in university buildings and multifamily houses, partly because clothing insulation worn inside office buildings was higher (Kumar, 2022). Thermal comfort field studies have been conducted in naturally ventilated and mixed-mode primary and secondary school classrooms in Australia during the summer with students aged 10-15 and 16-18 years respectively (Kim and de Dear, 2018). Based on the results, it was estimated a range of indoor temperatures for 80% acceptability of 16.2 K for primary school and 19.4 K for secondary school. The wider range of acceptable temperatures than the ASHRAE 55 adaptive model was attributed to students' lower sensitivity to temperature changes and a wider range of thermal sensations being perceived as acceptable (Kim and de Dear, 2018). For educational buildings, it is likely that adaptive thermal comfort models will differ according to educational level. For example, results from a field study in a naturally ventilated classroom during the heating season in Pisa, Italy, showed that students' ability to adapt to the thermal environment increases with higher levels of education, i.e. primary school children are more passive in relation to their thermal environment than their counterparts (Torriani et al., 2023). In addition, the neutral temperature increased on average by 1°C at each level of education from primary to secondary, high school and university (Torriani et al., 2023).

In the scientific literature, most field studies on thermal comfort of mixed-mode buildings have been conducted in office, educational and residential buildings (Földváry Ličina et al., 2018; Kim and de Dear, 2021; Peng et al., 2022; Bienvenido-Huertas et al., 2023). There is a lack of research on other building types and therefore a gap in understanding how adaptive comfort models including their upper and lower limits of acceptability would differ from existing models.

Conclusions

This paper has presented ten questions and answers concerning the application of adaptive thermal comfort in mixed-mode (MM) buildings. The concept of adaptive thermal comfort has gained significant attention in recent years as a sustainable approach to building design and operation. This adaptive approach of aligning indoor comfort with external climatic conditions is relevant in the context of MM buildings, which combine natural ventilation with mechanical conditioning systems to simultaneously optimise indoor environmental quality and energy efficiency.

Extrapolation of current trends suggests that the demand for cooling in buildings will increase threefold by 2050, underscoring the urgent need for a fundamental re-think of how we design for comfort. The integration of adaptive thermal comfort in MM buildings offers a compelling pathway towards sustainable and resilient building practices.

Mixed-mode buildings should follow the 'hierarchy of adaptive opportunities', maximising the application of natural ventilation and allowing occupants to control their thermal environment, for example by operating windows. Beyond the maintenance of minimum ventilation requirements, mechanical systems should only be used as a supplementary means of controlling indoor thermal conditions within adaptive comfort thresholds, i.e. HVAC systems should be thought of as the discomfort remedy of last resort. This approach not only attenuates energy demand, but it also mitigates the deleterious impacts of active cooling while simultaneously enhancing occupant satisfaction and health.

The findings of this 10-question paper indicate that the implementation of MM buildings is both feasible and advantageous in both new construction and existing building stock, offering a versatile solution for various building typologies and climatic zones, considering both current and future climate scenarios. We have also emphasized the importance of balancing automated controls with individual adaptive opportunity to optimize comfort and energy performance. There is a pressing need for developing guidelines incorporating various MM design and operation strategies tailored for specific climate contexts, building typologies, and occupancy patterns. International thermal comfort standards (e.g. ASHRAE 55, EN 16798-1) should explicitly allow the use of adaptive thermal comfort for mixed-mode buildings during both natural ventilation and active cooling/heating operation.

By addressing the ten questions in this paper, this study contributes to a broader understanding of MM strategies and greater awareness of how, when, and where they might be appropriate, thereby supporting the transition to a low-carbon and climate-resilient built environment. Future research should continue to investigate different mixed-mode strategies in various climatic and building contexts regarding multiple aspects, including human factors (e.g. comfort, well-being, performance), building (e.g. energy demand, sustainability) and planetary levels (e.g. regenerative and restorative buildings).

Biography

Ricardo Forgiarini Rupp:

Ricardo is a Civil Engineer holding a master's and a PhD in Indoor Environment and Energy Efficiency in Buildings from the Federal University of Santa Catarina, Brazil. Dr Rupp has working experience in various climatic contexts from the tropics in Colombia and Brazil, the subtropics in Australia and Brazil, to colder climates in Scandinavia. He has worked at the Technical University of Denmark, conducting research on topics related to indoor environment, ventilation systems, occupant behaviour, and sustainable buildings. Currently, he works in the Knowledge Centre on Daylight, Energy & Indoor Climate at VELUX A/S. Ricardo has been working with mixed-mode buildings for more than fifteen years in both academia and consultancy settings. He has conducted extensive field studies on thermal comfort in mixed-mode buildings. Dr Rupp has developed adaptive thermal comfort and behavioural models of adaptive actions for mixed-mode buildings in temperate climates. He has also quantified the effect of contextual (e.g. ventilation type) and individual differences (e.g. sex) on occupants' comfort perception. Ricardo has also performed a number of consultancies on mixed-mode buildings with diverse scales and uses (e.g. schools, offices, hospitals, residential).

Jungsoo Kim:

Jungsoo Kim is an Associate Professor of Building Science in the School of Architecture, Design and Planning, The University of Sydney. His research explores occupant-building interactions, aiming to provide a deeper, more nuanced understanding of how environmental factors influence user behaviour, comfort, and concomitant energy demand in buildings. He conducts research and teaching in the areas of the design and operation of high-performance buildings.

Jørn Toftum:

Jørn Toftum is a professor and section head at the Technical University of Denmark. For more than 30 years, he has carried out research to describe how the indoor environment influences the comfort, health and performance of humans. His research includes numerous laboratory studies and comprehensive surveys in daycare centres, schools, offices and dwellings to describe associations between indoor environment exposures and people's responses and behaviour.

Gail Brager:

Gail Brager, PhD, is Professor of Architecture at the University of California, Berkeley. Professor Brager serves as the Director of the Center for Environmental Design Research, and Director of the Center for the Built Environment, a research collaboration between the university and over 40 industry partners focused on improving the energy performance and environmental quality in buildings, with a focus on the workplace. Professor Brager conducts research and teaching across multiple dimensions of sustainability addressing the design, operation, and assessment of buildings, with a focus on thermal comfort and adaptation, occupant well-being, natural ventilation and mixed-mode buildings, and personalized environmental control. She recently co-authored a book called Experiential Design Schemas, interesting building and health sciences with architectural design and aimed at expanding the joy and nature connections in buildings. She is also an ASHRAE and ISIAQ Fellow.

Richard de Dear:

Richard de Dear's PhD research career in indoor environmental quality stretches over four decades in Australian, Danish, and Singaporean universities, and he is currently the most highly cited researcher in the peer-reviewed literature on 'thermal comfort' (Scopus). He is the founding Director of the IEQ Lab at The University of Sydney. His adaptive comfort model features in ASHRAE Standard 55 (2004 till present) and various building codes, standards, and design guides around the world. He co-chaired the IEA Energy in Buildings and Communities Annex 69 on "*Strategy and Practice of Adaptive Thermal Comfort in low-Energy Buildings*" (2015-2022) and is currently serving on the WHO-WMO technical advisory panel on indoor heat and health. Dr de Dear is a Fellow of the International Society of Indoor Air Quality and Climate (ISIAQ) and in 2024 he was awarded the Pettenkofer Gold Medal, ISIAQ's highest accolade, for his contribution to the indoor air sciences.

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