



Thermal comfort of heterogeneous and dynamic indoor conditions — An overview



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ABSTRACT

The buildings sector, being a leading energy consumer, would need to lead in conservation efforts as well. There is a growing consensus that variability in indoor conditions can be acceptable to occupants, improve comfort perception, and lower building energy consumption. This work endeavours to scrutinise and summarise studies that examined human thermal and comfort perception to such variations in the indoor environment: spatial transients, non-uniformities, and temperature drifts. We also briefly discuss personalised comfort systems since they work on an occupant's micro-climate and create non-uniformities in the indoors. Perusal of works done on effect of non-thermal factors on thermal comfort, point to the need for synchronizing the overall indoor environment's quality — in terms of décor, air quality, lighting etc. — to improve occupant thermal comfort. Essence of the overall discussions come out to be that indoor thermal environment can be variable and still agreeable, implying existence of energy saving avenues, hitherto precluded from earnest consideration.

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1. Introduction

About 40% of our society's energy demands stem from buildings [1,2]. It stands to reason that in any move towards a greener future, the buildings sector will have a major role to play. The IPCC Working Group III too concluded that buildings hold the potential for maximum reduction of emissions in an economic fashion [3]. The attempted 'greening' of buildings must take into consideration indoor comfort of the occupants involved. And comfort has a strong correlation with health and productivity of the population [4]. In this aspect, thermal comfort standards have a role to play and at present they are in a transitional period with foreseeable further rapid modifications. An example of such transition, over the past decade, would be the introduction of adaptive comfort standards. Traditionally the thermal comfort standards had in mind mechanically conditioned buildings, with temperatures held within narrow limits. Extrapolating these standards to low energy buildings, that rely on passive strategies for indoor comfort, does not provide the desired effect. Departing from the focus of near steady state conditions of mechanically conditioned buildings opens up the avenues for reworking the standards towards altered realities of

building energy and comfort.

1.1. Context and methodology

One continuing conundrum of the built environment is that we live in the same houses, with unchanged expectations of thermal comfort, while the outdoors are undergoing staggering changes, be it diurnal or seasonal. Can the same building enhance comfort for all outdoor conditions? Across such external variations, instead of keeping indoor thermal conditions constant, could it be healthier to harmonize with the natural patterns? It could definitely be more energy efficient.

Occupants appreciate a reasonable amount of variability in the indoor environment — related to the senses such as light, sound, and temperatures — since a completely uniform environment becomes tedious by being devoid of considerable sensory stimulations [5]. A more dynamic thermal environment (both spatial and temporal components), pushing the boundaries of comfort zones, inculcating features of the natural outdoors, would be able to provide occupants with the required thermal comfort, along with moments of thermal delight and positive stimulation. Such environments would also contribute to energy savings. This change in design philosophy is complementary to just employing higher efficiency HVAC systems and personalised control. In light of recent developments at the world stage, focusing on even more ambitious

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goals for emission reductions [6], a heterogeneous and more flexible comfort zone could be consequential by providing further latitude for reducing building energy requirements.

This work is an attempt to summarise works in the field of human thermal comfort, as related to different spatial and temporal transients and the consequent comfort implications. Fig. 1 gives an impression of this work's layout, with thermal comfort of heterogeneity at the centre, surrounded by the sub-topics deliberated upon and their perceived interconnections. Section 2 discusses inputs from current international standards — along with any supporting literature — regarding allowable variations and non-uniformities in indoor environments and on those salient features of the standards that advocate a broadening of comfort zone. Starting with broad search parameters such as 'human thermal comfort' and 'thermal sensation', Section 3 summarises such works that involved human participants being exposed to dynamic or non-uniform thermal environments, both under field and laboratory conditions. Related literature on thermal sensation and comfort of local body parts are also summarised. We further discuss some recent works on the concept of alliesthesia and what it implies for comfort under heterogeneous situations.

Since personalised comfort systems also tend to bring about certain non-uniformities, their potential at extending comfort zones is also considered succinctly in Section 4. This section also briefly digresses into literature regarding differences among occupants in terms of thermal perception, effect of availability of occupant control, and role of alliesthesia in personalising comfort. Section 5 regards how non-thermal aspects of an indoor environment may impact thermal comfort and their possible contributions to creating non-uniform, comfortable indoors. We end with a brief summary of the features of indoor comfort reviewed and briefly discuss some future outlook.

Being an attempt to examine the inherently multidisciplinary and multifaceted nature of thermal comfort, brief digressions into occupant physiology, psychology, and behaviour are made. The conceivable inter-linkages are depicted in Fig. 1. Such discussions are based on findings in literature and aim to better explain comfort perceptions and/or thermal sensation. But these discussions are kept brief and we refrain from positing independent positions as physiology and psychology are not our forte. It is endeavoured to retain the focus on indoor thermal comfort aspects and related

implications. This work also does not attempt to provide an overview of thermal comfort research in general, which has been examined by many excellent reviews [7–9]. At the same time, we do not explore the field of thermophysiological models for thermal comfort prediction, which has been analysed and summarised by works such as [10–12].

2. Inputs from current international standards

2.1. Comfort zones for indoor occupants under static and uniform conditions

At 1.1 met, 0.1 m/s air velocity, ASHRAE Standard 55 recommends comfort zones of ~20–24 °C for winter clothing (1 clo) and ~23.5–27 °C for summer clothing (0.5 clo) [13] — a reasonably wide territory with explicitly acknowledged seasonal variations. Recommendations from EN15251 and ISO7730 are of similar nature. Enhanced air speeds can stretch the summer limits to ~30 °C. Since at typical indoor heating temperatures, air flow would just enhance heat loss from skin, convective heating is a lot less desirable and cannot extend winter comfort [14].

A reduction of clothing resistance by 0.1 clo corresponds to an increase of 0.8 °C in operative temperature and vice versa [13]. Unlike other similar options (having fans, windows, blinds, radiant heaters etc.), flexibility in occupant clothing is probably the only true '0' cost option.

2.2. Local discomfort, asymmetry, ramps and drifts

ASHRAE Standard 55 explores only certain specific transient scenarios [13]. According to the standard, impact of prior exposure/activity levels may last up to 1 h. Requirements presented regarding local thermal discomforts, from causes like draft, thermal asymmetry etc., are for occupants with clothing insulation less than 0.7 clo and activity level less than 1.3 met. Above these levels, no local discomfort limits are prescribed. It is also mentioned that occupants are more sensitive to local issues in a cooler environment. EN15251 [15] refers to the ISO 7730 [16] (or specific national codes) for the local thermal discomfort criteria and temperature drifts/ramps. ISO 7730 proposes use of PMV model, with reasonable approximation, if one or more variables have minor fluctuations, as

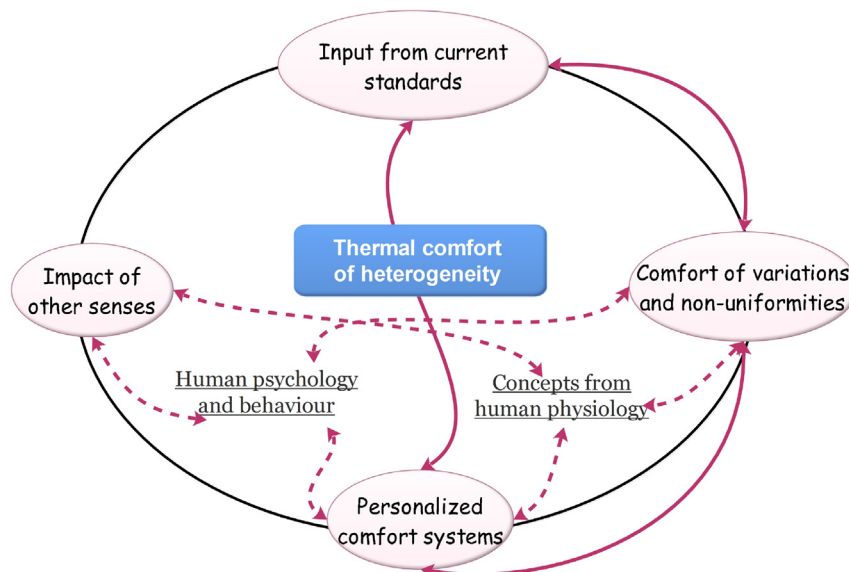


Fig. 1. A representation of the article's architecture and the interconnection between different sections.

long as hourly time-weighted average values of the variables, over the past hour, are used. Unfortunately, the standard does not go on to explicitly quantify what may be considered as minor fluctuation for the different variables.

Draft sensitivity is greatest for portions of body without clothing — head region (head, neck, and shoulders) and leg region (ankles, feet, and legs) — and Standard 55's requirements are given for draft in the head region with airflow from behind. These requirements are proposed to be conservative for other body parts and airflow directions. At operative temperatures below 22.5 °C, average air speed caused by building, fenestrations, and HVAC system should not exceed 0.2 m/s.

The radiant asymmetry and thermal stratification requirements as per Standard 55 are depicted in Fig. 2. Requirements for thermal stratification are for situations where head is warmer than feet. Temperature differences in the other direction are rare and are also perceived favourably by occupants. Floor temperatures need to be limited between 19 and 29 °C.

From Fig. 2, the important thing to observe is that with appropriate positioning of radiant sources, asymmetries between 5 and 23 °C are allowable and can be included in building design. Nonetheless, actual energy savings would result only if these asymmetries are due to design and not due to flaws in design.

Standard 55 suggests that any temperature fluctuations under control of the occupant do not adversely affect comfort and hence does not cover such situations. Step-changes due to moving from one location to another (say, room to hallway) are allowable as long as each individual condition is within comfort zones of the static model. ISO 7730 proposes the following regarding step-changes:

- A step-change in t_{op} is instantaneously felt
- The new steady state is immediately attained following an up-step
- Following a down-step, the thermal sensation drops instantaneously and takes about 30 min to rise to the steady level

As per ASHRAE, cyclic variations are defined as situations with period of less than 15 min and under such conditions, peak-to-peak variation in operative temperature (t_{op}) of up to 1.1 °C is allowed [13]. ISO 7730 puts such limit at 1 °C [16]. Temperature drifts are defined as such changes in t_{op} that are not controlled while ramps are controlled variations. For this work, we would be using the term 'temperature drift' for both effects. Maximum temperature drift over 4 h duration is limited up to 3.3 °C as long as the variations are within 1.1 °C, 1.7 °C, 2.2 °C, 2.8 °C for each 15 min, 30 min, 1 h, and 2 h respectively [13]. ISO 7730 recommends that for drift/ramp of less than 2 °C/hour, steady state analysis can be applied. The implicit constraint is that both starting and end points for the drift

have to be comfortable, from steady state analysis.

2.3. Adaptive comfort models

The concept of Adaptive Thermal Comfort (ATC) depends on occupants' ability to adapt to their ambient. Based on such adaptations, a model is proposed of thermal comfort temperature varying linearly with an outdoor temperature index. The outdoor temperature index used may vary from one model to other and some frequently used ones include monthly mean temperature, daily mean temperature, seven day running mean temperature, seven day average of mean temperatures etc. Around the comfort temperature determined on a particular day, for 80% occupant acceptability, a comfort zone width of $\pm 3.5^\circ$ [13] or $\pm 3^\circ$ [15] is allowed. For European offices with heating or cooling systems, Nicol and Humphreys [17] gave a $\pm 2^\circ\text{C}$ zone around the adaptive comfort temperature for 80% occupants' comfort. Occupant adaptations have been categorized as physiological, behavioural, and psychological. Over the past decade, much work has been done on the adaptive comfort models and several adaptive comfort models have been proposed [18], along with some controversy regarding the basis of ATC [19].

Adaptive comfort models in current standards are limited to sedentary level activities (≤ 1.3 met), though, this metabolic limit may not necessarily be inviolable [20]. No limitations are specified for humidity levels, air velocity, and clothing, based on the assumption of occupant control and acclimatization. Occupants can adjust to operative temperatures up to 29 °C by utilising just clothing adjustments [21]. Local non-uniformities, drifts/ramps etc. are not scrutinized also based on assumption of occupants' ability to modify their immediate environment.

ASHRAE Standard 55's ATC guidelines may be applied to buildings where: operable openings to the outdoors that can be readily opened and adjusted by occupants are present, no mechanical cooling or heating system is operational, and occupants can adapt their clothing over a breadth of at least 0.5 clo. Under the Dutch Adaptive Temperature Limits guideline (ATG), in buildings without an active cooling system, with operable windows, and no imposed dress codes (Class 'Alpha'), the comfort requirements can be more relaxed during warmer outdoor conditions [22,23]. The buildings with limited occupant control are classified as 'Beta' [22]. The ATG does recommend an adjustment in comfortable operative temperatures, for both types of buildings, if activity level departs from 1.4 met or if clothing levels depart from 0.5 clo in summer and 1 clo in winter [23].

In lieu of occupant activity level, clothing, and perceptions varying across different rooms in residences, Peeters et al. [24] proposed a variant of adaptive comfort algorithm, with specified

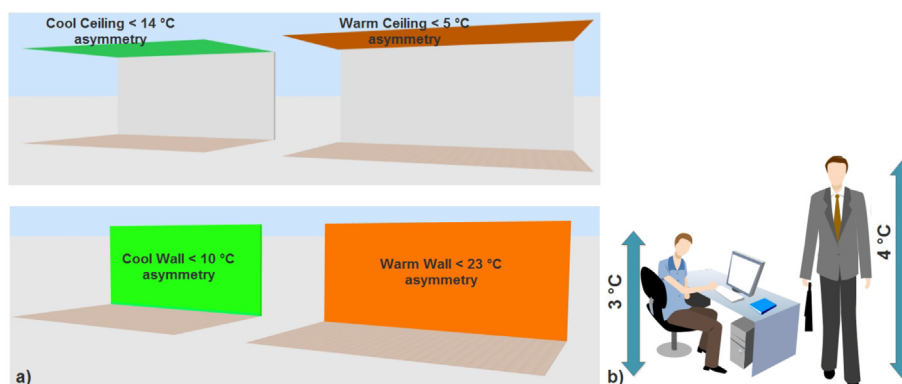


Fig. 2. ASHRAE Std. 55 on allowable a) radiant asymmetry and b) thermal stratification indoors.

recommendations for each type of room in homes. Bedrooms can have a lower limit of temperature to the point of 16 °C and an upper limit of 26 °C, assuming no enhanced air velocity. Upper temperature limit for other rooms can go up to 31 °C for 80% occupant acceptability while lower limit is 18 °C. Later studies have also confirmed the difference in preferred occupant temperature across different rooms of residences [25].

The Chinese adaptive comfort model for free running buildings takes the form of the Adaptive Predicted Mean Vote (aPMV): [26,27].

$$aPMV = \frac{PMV}{1 + \lambda \times PMV} \quad (1)$$

λ is the adaptive coefficient, a reflection on the adaptation level of a population, and depends on the climate and building type [27]. For example, in cold/cool regions, for residential buildings, $\lambda \sim 0.2$ when $PMV \geq 0$, while for meeting rooms in warm regions, $\lambda \approx -0.28$ when $PMV < 0$. Adaptation level is considered to be high in hot, humid environments and comfortable environments on the warmer side of neutrality, while it is low for cool, dry environments and comfortable environments on the cooler side of neutrality [28].

The extended PMV model, or ePMV, introduced by Ref. [29] tries to account for the expectations of occupants (a form of psychological adaptations), based on local factors like climate and prevalence of mechanical conditioning. However, the choice of 'e' value for specific locations, used in ePMV models to denote expectancy factor, has been much debated and as such, ePMV model has found only limited usage. The model does present an important turning point when rational models started to try and emulate the principle behind adaptive thermal comfort principles. Results from some studies indicate that comfort models of similar form and adaptive comfort equations, relating comfort temperature to outdoor conditions, may also be applicable for air conditioned spaces [17,30,31].

2.4. Humidity and comfort

Standard 55 does not provide a lower limit for humidity whereas upper limit is put at 0.012 kg/kg dry air, at 1 atm. Non-thermal factors — dry skin, eyes etc. — place limits on lower limit of humidity, though the standard does not go into these details. Humidity has a minor role to play in overall body heat loss, except for certain extreme conditions [32]. With operative temperature within acceptable limits, thermal perception and skin temperature and wettedness are generally not affected much by humidity [33,34]. Neither is subjective performance rating, though

higher humidity levels can result in subjects feeling more tired [34]. This lack of sensitivity to humidity levels is even more conspicuous for acclimatized individuals [32]. Hence, air-conditioning systems can save energy simply by maintaining temperature set-points within a broader envelope of humidity [35,36].

At operative temperatures beyond the upper comfort limit of temperature and/or activity levels higher than sedentary values, humidity levels can impact skin temperature and wettedness [33], perceived air quality [37] and subjective thermal sensation [38]. By manipulating the skin area fraction over which sweating is taking place, sweat evaporation can be ensured over a wide range of humidity conditions [32]. The resultant increase in wetness of skin, while advantageous for thermoregulation, is unlikely to be rated well in terms of subjective sensation. During temperature transients of neutral to warm (hot), sweating response takes input from both core and skin condition and the time taken for onset of sweating depends on rate of temperature rise [39]. Rapid fluctuations of RH, of less than an hour periodicity, may not be noticed by occupants, as opposed to slower variations [40].

2.5. Increasing air velocity for cooling needs

Standard 55 stresses upon enhanced air velocity to improve comfort in warm conditions. These recommendations are summarised in Fig. 3.

Greater air velocity can compensate for rise in temperature and humidity [41,42], improve air quality perception [43] and ensure performance level in warmer environment [44], and help the body attain a stable thermal state [45]. Occupant controlled air velocity can offer welcome thermal comfort [46] and reduce skin temperatures [41].

That raising air velocity over 0.8 m/s in an office environment can cause disturbances, due to loose paper and such other light objects getting blown around, has been long discredited [47]. As an energy saving alternative, flows of higher turbulence intensity can be used to reduce the peak air velocity required for comfort [48]. Data remains ambiguous on the utility of fans during heat waves but it has been suggested that a fan can improve heat loss when ambient temperature is below 35 °C [49].

Even with higher activity rates, enhanced air velocity can ensure thermal comfort levels at warmer temperatures though the temperature compensation is not as much as seen at lower activity levels [50,51]. Beyond thermal comfort, air movement also improves air quality perception for active individuals [51]. At higher physical exertion, the range of accepted air velocity also gets wider [51]. Activity rate also significantly lowers draft sensation for

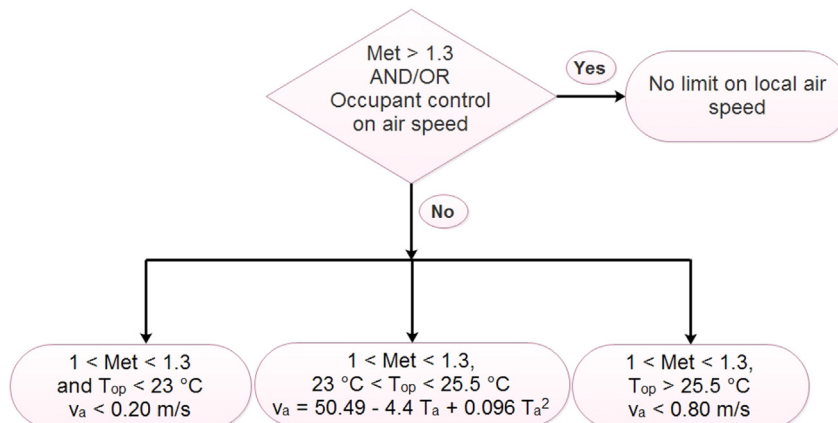


Fig. 3. Recommendations regarding indoor air velocity in ASHRAE Std. 55.

people working in low temperature environments [52,53] though the relief in draft sensation may be limited to the regions of body with muscles active during the specific activity [53]. While higher activity rates do not carry much import for typical comfort conditioning, these findings are relevant for determining air velocity levels in transitional spaces like hallways, lobbies, waiting rooms etc., where activity level is often beyond sedentary levels.

Increasing air velocity without proper additional considerations can lead to adverse effects. In temperatures of 34 °C, the air velocity required for retaining comfort levels can be 2 m/s or over [46], though, under such conditions, air movement may just spread the heat around the room and enhance convective heat transfer to the body [46,54]. Along the same lines, sound produced by fans running at their peak speed can be a source of irritation [49] and localized air flow may cause issues with eye dryness [55].

2.6. Occupant satisfaction and breadth of comfort zones

Arens et al. [56] showed that the different ‘classes’ of temperature requirements, based on allowed breadth of indoor temperature variations, do not produce appreciably different results for occupant comfort and acceptability. They found that tighter control did not give appreciably better satisfaction, while being 12–30% more energy intensive. Desire of a thermal sensation other than neutral and satisfaction with thermal sensations beyond the ± 1 of ASHRAE voting scale are not uncommon [57–60]. Average limits of occupant discontent in conditioned buildings is 19–26 °C [43,61], and for free running buildings with ceiling fans is 19.5–28 °C [43]. Within these limits, occupant acceptability is more or less unvarying, though dropping off sharply beyond the limits. So, there is no particular advantage in HVAC systems targeting a single “optimum” temperature.

Indoor conditions maintained within narrow zones could gradually atrophy thermoregulatory ability and adaptive capacity of the occupants [44]. The ASHRAE Standard 55, in its more recent forms, has also been advocating broader comfort zones, particularly raising the upper comfort limit, influenced by greater allowable air velocities.

3. Comfort of variations and non-uniformities

As discussed in Section 1.1, the present concern is for designing more energy efficient and comfortable buildings and thermal heterogeneity may contribute positively towards these goals. Studies show that subjective votes of “Very comfortable” are not elicited during “neutral” conditions or conditions of uniform changes over the whole body, but during transitions or in non-uniform conditions where comfort feeling of one body part alleviates overall discomfort [62,63]. We discuss in this section how people respond to variable conditions, spatial non-uniformities, and temperature drifts.

3.1. Transients

3.1.1. Transients and thermoreception

Under static conditions, error signals from core temperature and mean skin temperature drive any thermoregulatory action while during transient episodes, the rate of change of skin temperature also plays a role [64]. It has been hypothesised that contributions from both skin and core temperature for thermal comfort perception are nearly equivalent [65]. This has the advantage of ensuring faster/better timed behavioural responses [66] because of skin's better intimacy with the ambient. Similarly, ability of cutaneous thermoreceptors to detect changes in temperature and temperature gradient across skin surface aid in improving response time of

skin's thermoregulatory feedback to changes in ambient [67]. Cold receptors are more abundant in the skin, while warm receptors are more numerous in the body core [68], making all cutaneous regions more sensitive to coolth than warmth [69]. Cutaneous cold receptors are closer to the skin surface and conduct information faster than the cutaneous warm receptors [68]. This possibly impacts the difference in perception of warm and cold transients [70,71], as further discussed in Section 3.1.2.

3.1.2. Spatial transients

When subjected to a sequence of different thermal conditions, the response of people to a particular ambient significantly differed depending on the sequence of previous environments they had experienced [72]. Thermal sensation and comfort ratings, during spatial transitions, often have an anticipatory effect and lead physiological responses [48,73,74]. A thermal sensation overshoot is said to occur when the response of participants immediately following that of a down-step (or an up-step) is lower (or higher) than the stable value under those conditions. Overshoots are most significant only in the first couple of minutes [71,75] and are stronger for larger step sizes [75,76]. Most studies have shown an overshoot to be present and more pronounced for a down-step [48,62,70,71,75–79] while being absent for an up-step [70,71,80,81]. Some observations have shown that cooling overshoots may occur only for strong cooling steps (~ 5 °C) [48,73], while overshoots for up-steps can occur for sudden changes of moderate step size (~ 3 °C) [73].

The initial overshoot in sensation could just be the perceived/anticipated relief in thermal stress [62]. Moving from a hot to a warm room or a cold to a cool room may thus induce a neutral sensation [82]. People moving between a conditioned cool environment and outdoors could have warmer perceptions of the outdoors than it actually is [83]. In a similar vein, people working in a location are likely to be less satisfied with their prevalent thermal environment, and have narrower thermal comfort zones, than people who are passing through, for example, staff vs passengers in an airport [84]. Local comfort and sensation overshoots are more obvious than any overshoots from whole body transition [62,63,85] and overshoots for comfort are more pronounced than those for sensation [63]. Head, chest, back, and calf are most sensitive to step-changes in temperature [75].

In addition to depending on direction of the transition (even when the magnitude is similar) [80,81,86–89], responses also depend on magnitude of the step change [74,90] and magnitude of the starting temperature [78]. Down-steps may result in greater changes in sensation than up-steps [70,75]. The subjective ratings of comfort and sensation also stabilise faster than physiological parameters (like skin temperature or skin blood flow) [62,71,73,74]. While some studies indicate that skin temperature stabilises faster after an up-step [80,87], others indicated a faster stabilisation after a down-step [74,75]. Certain physiological responses like skin temperature and heart rate variability (HRV) can be more sensitive to down steps [74]. Xiong et al. [74] report that sudden temperature step-up may lead to a rise in percentages of self-reported symptoms like perspiration, eye-strain, dizziness etc. while such reports drop off with a sudden step down [74].

During a step change, thermal sensation vote (TSV) has been found to be best correlated with variously as skin temperature [71,77,78], derivative of skin temperature with respect to time [63], maximum difference between local thermal sensations [91], temperature difference between the two spaces [92], and rate of heat loss from the body [75,80]. Thus, there is little consensus on evaluating TSV during step-changes.

When activity level of a person changes, the thermal sensation change is immediate, with about 20 min required for the TSV to

stabilise [93]. Goto et al. [93] suggest a weighting of metabolic rates over the past 20 min to arrive at an average metabolic rate that can be used in steady state comfort models to predict thermal sensation of the individual: 0.65 weightage for activity from past 5 min, 0.25 for past 5–10 min, and 0.1 for past 10–20 min. During activity, blood flow to skeletal muscles rises as activity level increases (can rise up to ten fold) [94]. But when the activity has to come to a sudden halt, blood flow levels fall off quickly leaving the heat trapped in these large muscles, which are slow-responding thermal masses. This has implications regarding local cooling requirements (focusing on limbs, where most of the large skeletal muscles are concentrated) for individuals who come to work by cycling/walking.

Table 1 presents the time taken by certain physiological and subjective responses to stabilise after a step-change, as reported in different works, with \bar{t}_{sk} symbolising the mean skin temperature. The data in Table 1 points to a transition time of 20–30 min, during which, the individual is still adjusting to the new conditions, both physiologically and mentally. Spaces through which transitions last shorter than this duration, could do with relaxed set-point controls.

Areas like lobbies, hallways etc., in typical commercial buildings, are examples of such transitional spaces. Occupant activity, behaviour, and attire in such spaces are more dynamic, making PMV predictions inaccurate [95]. Users in transitional space can adapt to a wider range of conditions and such spaces do not need precise HVAC control (or, depending on weather, no conditioning at all) [72,96]. Having transition spaces at an intermediate temperature can also help reduce the physical distress of transiting directly between a conditioned building and the outdoors. [81] showed that for people moving between an office and the adjacent veranda, TSV differences are not significant and any discomfort is short lived. To avoid overwhelming burdening of thermoregulatory system, the magnitude of step changes from main area to transition spaces may be limited to $\pm 3^\circ\text{C}$ (Fig. 4) [71,80,89,90].

Table 1
Stabilising time for subjective and physiological responses.

Source	Parameter	Stabilising time (min)
Arens et al. [62]	TSV and TCV	10
Yu et al. [85]	Foot TSV	5
Nagano et al. [78]	\bar{t}_{sk}	~20
Chen et al. [71]	TSV	30
Horikoshi and Fukaya [87]	\bar{t}_{sk}	10
Du et al. [80]	\bar{t}_{sk}	Down-step 18–29 Up-step 11–18
Liu et al. [75]	TSV and \bar{t}_{sk}	~20
Yu et al. [90]	TSV	~10
Yu et al. [76]	TSV	~10

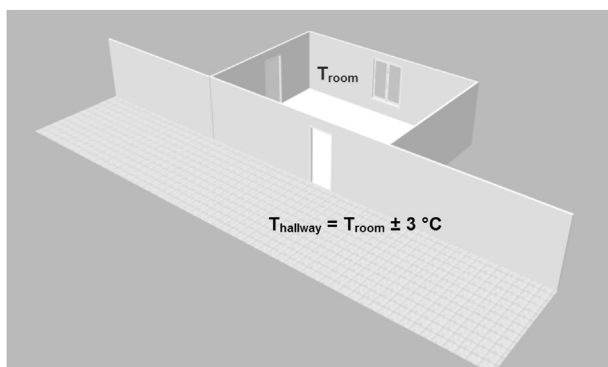


Fig. 4. Relaxed thermal comfort requirements for transition spaces.

3.1.3. Temperature drifts and cycles

Rohles [97] recommended considering time of exposure as the seventh comfort variable, in addition to the six commonly considered ones. Temperature drifts have a separate dimension for comfort considerations. Standards, like ISO 7730 and ASHRAE Standard 55, give some specifications regarding acceptable magnitudes of drifts. We discuss here some further results from experimental works. The range of cyclic temperature deviation perceived as tolerable by occupants reduces with the frequency of those cycles [98]. For rapid changes in ambient temperature, the changes in skin temperature were smaller, which could be because of a thermal lag of the skin that meant it could not keep up with ambient conditions [88,99]. Studies from Berglund and Gonzalez [86] showed that a rise from 25 to 27 °C at the rate of 0.5 K/hour is not noticed by occupants dressed in light (0.5 clo) or moderate (0.7 clo) clothing and with heavy clothing (0.9 clo), such ramps get noticed after 3 h. Similarly, ramps of 1–1.5 K/hour go unnoticed over the first hour. Negative ramps of 0.5 K/hour go undetected with occupants dressed in 0.7–0.9 clo. But for longer exposures — 4 h — even ramps of 0.6 K/hour become noticeable [100]. For up and down ramps of 1.2 K/hour, predictions from PMV model could yet be useful [101].

A warmer temperature reached following a shallower ramp may be perceived to be the same as a slightly lower temperature reached by a steeper ramp, steeper ramps leading to quicker reactions [102]. As per Rohles et al. [103], cyclic variations are acceptable where air temperature variations are 3.3 K/hour or smaller and the peak to peak variation magnitude is less than 3.3 K. Greater variations are unacceptable even when within the comfort zone. For temperature change rates of 4 K/hour, Jacquot et al. [104] have reported only non-significant changes in such physiological parameters as blood pressure, heart rate, and core temperature. As regards cyclic variations, though fluctuating air temperatures could improve comfort, introducing such fluctuations in the field is a difficult strategy to practically implement [48]. Fluctuating air temperature may even provide better thermal satisfaction and reduce occupant stress, as compared to fixed set points. The work of Miura and Ikaga [105] showed this for simulated office settings, while varying the temperature from 28 to 26 °C, and back, as compared to keeping conditions fixed at 26 °C. Temperature ramps did not show any consistent or discernible effect upon the productivity parameters examined for office workers [101,102]. Also, temperature fluctuations, as may be experienced during a direct load control event, do not seem to impact occupant cognitive performance [106].

One of the methods suggested for energy savings in intermittent occupancy situations like offices is to let the cooling set point temperature drift towards end of occupancy period [107]. Zmureanu and Doramajian found that allowing the space temperature to drift to 27 °C after 3 p.m. does not adversely affect occupant comfort. At least two different field studies done in actual offices showed that the acceptable comfort temperature for occupants was higher in the afternoon by more than 1 °C [108,109]. These two studies were conducted in locales with very different climatic, social, and economic backgrounds and yet, both studies showed a higher comfort temperature being preferred in the later half of an office day. Small drifts of temperature towards day end may not be noticed by occupants for around 4 h [86,100]. Before occupants respond to such drifts, if the HVAC system initiates a corrective drift back to neutral conditions, a positive comfort response could be elicited from occupants [62]. Such positive response may be attributed to a feeling of spatial alliesthesia [110,111], discussed in Section 3.3.

3.1.4. Circadian rhythm of body: a diurnal comfort cycle?

Mean oral temperature of human beings is close to 36.8 °C with

diurnal variations of 1 °C, a nadir around 4 a.m. and the zenith between 4 and 6 p.m. in the evening [112]. Circadian rhythm of core temperature in human beings is internalized and heat generation in the body co-acts with heat loss mechanisms to ensure this rhythm, even without variations in activity level due to sleep-wake cycle [68,113]. During periods of declining core temperature, average skin temperature increases to aid heat loss [68,114].

Circadian rhythm of heat production, core temperature, and heat loss are out of phase with each other [68,113,115–118] and this helps with sustaining the diurnal variation, with primary contribution coming from heat loss rhythm [68,114,119,120]. The core temperature increases while heat production is more than heat loss, and vice-versa [113]. Building occupants are thus in a “heat gain” mode in the morning (as the core temperature climbs) and in a “heat loss” mode in the evening [120–122].

Subjective thermal sensations (in terms of preferred temperature) and behavioural responses have also been reported to have a circadian rhythm [117,121,123] with minima pre-noon and maxima during late evening. This can lead to a warmer preferred ambient temperature during afternoon, compared to morning (by about 1.5 °C) [123], minimally dressed subjects choosing to dress quicker and in thicker clothing during morning than in evening [124] etc. It would be interesting to examine if the circadian rhythm of human body can be used to establish a rhythm of indoor conditioning temperature that keeps track of the outdoors and thus saves energy. Such a strategy would be complimentary to the late afternoon drifts discussed in Section 3.1.3.

3.2. Non-uniform environments

Non-uniformities in an indoor environment may be intended or unintended. Thermal comfort standards do discuss such non-uniformities as radiant asymmetry and thermal stratification. In non-uniform environment, consideration for local sensations becomes much more important than in uniform conditions. For uniform thermal conditions, overall thermal sensation, comfort, and acceptability have a strong correlation while under non-uniform thermal conditions, overall thermal acceptability and comfort maintain a close correlation, with thermal sensation dropping out [59]. The temperature in immediate vicinity of occupants can be 0.5–1.5 °C lower than the room's average temperature [125]. This would impact individual evaluation of a common work place. Local non-uniformities can also result from occupant posture and clothing ensemble. Posture of an occupant, in tandem with a pumping effect of the clothing ensemble, and a wick effect produced by certain clothing to enhance evaporative cooling, can change the effective clo values and make it dependent on what body part is being covered by the particular fabric [126,127]. Body parts with greater clothing insulation are likely to be warmer [128] and this asymmetry due to clothing is most prominent for the foot [129].

Early studies from Fanger et al. [130] indicated that radiant asymmetry did not impact the preferred operative temperature of people. Local cool/warm sensations that the experiment participants did experience were not judged as uncomfortable and the variation of local skin temperature also did not impact the mean skin temperature and core temperature. As radiant heat transfer is dependent on orientation and view factors, spatial arrangement of heat sources impacts the performance of radiant systems [131,132]. Similar magnitudes of radiant asymmetry have a greater impact on thermal sensation when frontal in nature than when side wise [133]. Body segments closer to warmer indoor surfaces (walls or window panes) are the most affected by radiant asymmetry [134]. With windows admitting enough solar radiation, the ambient can be maintained at a temperature 1.5 °C below neutral while PMV

values would still stay at 0.5 [135].

The bed represents a much experienced non-uniform environment for every person. Sleep quality, as evidenced by EEG measurements, was not found to be statistically different for bed room temperatures of 50 (10), 70 (21.1), and 90 (32.2) ° F (°C) [97]. Song et al. [136] observe that with proper bedding and quilt, the sleeping environment can have a resistance close to 4 clo, very different from the values observed in other situations. This meant that participants in their study gave good ratings in terms of both thermal sensation and comfort for room temperatures between 14 and 18 °C. These values are close to the lower adaptive comfort limits, suggested by Peeters et al. [24] for bedrooms (Section 2.3).

3.2.1. Thermal sensation in non-uniform ambient

Under steady, uniform, and neutral conditions, core temperature may not have much influence on thermal sensation [104], as it keeps stable and is not affected by local thermal stimuli [137]. When situations are otherwise, body parts closer to the core have greater contribution to whole-body sensation than the extremities [62]. Cool discomfort is believed to have local origins and relates best to mean skin temperature, while warm discomfort has a global origin and best correlates with sweating [77,138]. In a paradoxical finding, Huizenga et al. [139] showed that in warm environments, local cool stimulus can raise core temperature and this response is faster, lasting longer, when applied stimulus is closer to the core. This finding has implications for contact based personalised cooling systems.

Thermal sensation under steady conditions, has been noted to track mean skin temperature [64,73,85,138]. Other propositions also correlate thermal sensation with rate of change of skin temperature, finger temperature, wrist temperature, finger-forearm temperature gradient, forehead-finger temperature gradient etc. [73,104,140]. Wang et al. [140] observe that finger temperature of 30 °C can be treated as the boundary between cool and warm sensation for both transients and steady conditions. Pellerin et al. [138] recommend mean skin temperature between 32.8 and 33.3 °C for comfort. And there is at least one reported study where no relation could be found between skin temperature and thermal sensation [141]. The variety of conclusions point towards an obvious lack of consensus in this regard.

3.2.2. Local sensations and comfort

Local sensations relate well to local skin temperature under overall neutral conditions [62]. Local discomfort at a single location does not lead to overall discomfort [142] though the least comfortable body part has the maximum impact on overall comfort and thermal sensation [62,143,144]. For cooler environments, overall sensation would follow the cooler local sensations while in neutral to warm conditions, overall sensation goes as the warmer local thermal sensation [145]. The number of body parts feeling uncomfortable has a strong relation with overall dissatisfaction. Zhang et al. [146] drew the line at 2 or more parts under discomfort for a significant proportion of occupants to feel an overall discomfort. Zhang et al. proposed to categorize overall comfort sensation, in terms of local comfort, thus:

- For transient thermal conditions, or occupant control on environment, or the second lowest local comfort vote being >–2.5, overall comfort rating is the mean of the two lowest and the highest local comfort votes
- Else, overall comfort rating is the mean of just the two lowest local comfort votes

The most sensitive body parts, in terms of impact on overall sensation, are: head, face, breathing zone, pelvis/abdomen, chest,

and back under neutral condition; head under warm condition; hands and legs under cool condition [62,137,146,147]. Cooling (or warming) of the limbs, on the other hand, does not impact overall sensation much [85,146,147]. In fact, feet-cooling can actually deteriorate comfort sensation in a warm environment as compared to no cooling [141]. Parts like the hand and feet have rapid fluctuations in vasomotor tone, leading to their skin temperature giving a fast response to environmental changes [88].

Most variation in inter-body part sensation levels occurs for cool environments, followed by neutral, and warm environments [62]. This is most likely because vasoconstriction in cooler environments increases local skin temperature gradients. Subjected to similar clothing insulation, more heat is lost from the limbs than from the torso [128], likely ascribable to higher surface area to volume ratio of limbs. Exposed skin surface, being in literally in touch with the ambient, can give a better feel of the thermal environment [148].

The weight of a local stimulus increases as the nature of the stimulus deviates from the thermal state of the whole body [147], thus making local sensation dependent on the state of the rest of the body. The same forehead condition may be rated as warm or cool depending on if the rest of the body is cooler or warmer respectively while foot cooling can reduce or improve comfort depending on if the body as a whole is cool or warm respectively [147]. For overall warm conditions, local body parts prefer cool sensation and vice versa [149].

3.2.3. Convection around the body

Area fraction of body parts has the major influence on convective and radiative losses from each part while local evaporative heat loss depends on sweat gland distribution [150]. Licina et al. [151] experimented with a manikin to develop an understanding of natural convection around human body. Their findings may be surmised as follows. Under warmer ambient conditions, the convective boundary layer (CBL) around human body slows down due to the reduction in temperature gradient. Clothing material can further reduce the peak velocity in the CBL, loose clothing more so than tight fitting ones. For a seating position, reclining backwards increases the peak velocity in CBL by 45% over leaning forward. These findings can add to explaining certain behaviour of occupants, like reclining back on their seats in warm environments, draught feelings being enhanced at low ambient (due to higher temperature gradient). At the same time, air streams that a human being breathes in (or out) have sufficient velocity to interrupt the thermal plume around one's body and thus potentially affect thermal sensation [152].

Experimenters have made detailed measurements of convective and radiative heat transfer coefficients of different parts of human body, using thermal manikins and have obtained broadly consistent results in the process [153–155]. Convective heat transfer coefficients can be higher for clothed body, compared to nude body at elevated air speed, while air movement can reduce the clothing insulation effect and increase heat transfer coefficient [154,156]. Local heat transfer coefficients for different body parts are different, even with experiments being conducted under controlled laboratory conditions. During forced convection, heat transfer coefficients were higher for the extremities than the core (up to a 60% difference). Wind directionality had little effect on heat transfer coefficient values. The higher convective heat loss potential from limbs, added to the fact that summer ensembles often leave arms and hands exposed directly to air movement, can at least partially explain the utility of enhanced air velocities in warm environments, without risking draught.

With the possibility of non-uniform, transient indoor environments being more energy efficient at achieving occupant thermal

comfort, research interest has peaked in thermal models that can replicate human response to such environments, viz. multi-node thermophysiological models [11]. The increased focus on multi-node models was also driven by the inability of PMV model to cope with local non-uniformities [157]. The rising interest in multi-node models and fast growth of computational power available to researchers has led to development of several intricate thermophysiological representations of the human body. Foda et al. [158] verified the thermal sensation predictions of three such models (the Fiala model, the UCB model, a multi-segmental Pierce model) against subjective votes of seated occupants in sedentary conditions and found a less than one unit average deviation on the sensation scale. Unfortunately, the rising level of computational sophistication of these models has not been complemented by enhanced physiological databases, for validation, and for better understanding of thermoregulatory functions [159]. And a further issue of course remains, which involves translating thermophysiological values into human sensation and comfort.

3.2.4. Non-uniformities of the human body

This section goes towards expressing the association between thermal perception of heterogeneous environments and inherent human physiology, as also depicted in Fig. 1. Relative contributions of different portions of the body to thermoregulatory effect is often debated. As a gross estimate, skin surface, deep abdominal and thoracic tissues, spinal cord, hypothalamus, and other portions of the brain each contribute roughly 20% to control of autonomic thermoregulatory defences while behavioural defences may have a much higher contribution from value of skin temperature [160,161]. Skin temperature contribution to thermoregulation is usually expressed in terms of a weighted mean skin temperature [162]. The idea of using weighted skin temperature may be justified thus: impact of localized cooling/warming of skin is not determined just by the local skin temperature but by the overall skin temperature. Local warming in a cold environment is considered comfortable even though the site of warming may reach a temperature above normal values. Hence, it is important to consider the state of the skin as a whole.

Cutaneous thermoreceptors are spread all over the body with dense distributions in face, hands, and feet — particularly, fingers and toes [67,163]. The thermal sensitivity across cutaneous regions of the body can differ many fold, with face being most sensitive and extremities the least, though a sensitive region is sensitive to both cold and warm stimulus [68,69]. Due to the differential distribution of receptors, the thermal sensitivity of different body parts, as fraction of whole-body sensation were documented by Ref. [164] to be: 0.21 for face, 0.21 for chest and back, 0.17 for abdomen, 0.15 for upper legs, 0.08 for lower legs, 0.12 for upper arms, and 0.06 for lower arms.

Warm conditions lead to homogeneous vasodilation all over skin, resulting in a more or less uniform skin temperature (even in presence of clothing resistance) and cool environments lead to cooler limbs than core due to vasoconstriction [63,77,89,129,139,140,145,165]. In a thermally neutral ambient, preferred local skin temperatures and width of comfort zone vary with body parts, for both genders, with width being wider for males [166]. Variation of local sensations and differences between cutaneous conditions for different body parts, under different air temperatures were reported by Yao et al. [145] and have been summarised in Table 2.

Certain body parts are particularly suited for exchanging heat with the ambient and this may be inferred from their structure: high surface-to-volume ratio, lack of hair, high density of cutaneous blood vessels, presence of arteriovenous anastomoses. Our limbs, for example, account for nearly 50% of body's skin surface area

Table 2
Difference between local skin temperature values at different air temperature.

t_a	Max $\Delta t_{sk,local}$	Max ΔTSV_{local}	Coolest part	Warmest part
21	6.2	2.0	Limbs	Head
24	5.5	1.7	Limbs	Torso
26	4.3	0.8	Limbs	Head
29	3.0	1.5	Limbs	Head

[167]. Towards the upper limit of thermoneutral zone, most of the heat loss from the body is through such organs. Arteriovenous anastomoses (AVAs) form a direct communication between arteries and venous plexuses. They are not found in most subcutaneous regions but where found, they are extremely dense, e.g., 500 units/cm² in nail beds of fingers and toes [168]. Regions of body with AVAs may be regarded as excellent heat exchangers and deserve special attention in design of personalised or local cooling/warming systems.

3.2.5. Fluctuating air flows

In many natural and biological systems, including the human body, a $\frac{1}{f}$ frequency — also referred to as pink noise — has been identified, which may play an important role in sustaining life and influences all biological rhythm, right down from cellular level, up to organism behaviour level [169]. Such a rhythm is present in natural wind and may explain why natural wind [170,171], or its artificially simulated version [44,48], can provide better comfort sensation than mechanical wind. An air flow with the right frequency can have a greater cooling effect than constant flow with the same average velocity [172]. This could be because cutaneous receptors may respond better to stimulus at certain frequencies [173], and since the dynamic response of these receptors have a greater magnitude [70].

We end this Section 3.2 with an attempt at summarizing some of the important and interesting aspects discussed in Sections 3.1 and 3.2, regarding thermal comfort in heterogeneous indoors. These have been tabulated in Fig. 5, for easy reference of the reader.

3.3. Alliesthesia

Alliesthesia, as a term, was coined by Michel Cabanac, using the Greek words *esthesia* (meaning ‘sensation’) and *allios* (meaning ‘changed’) [174]. Any thermal environment has a descriptive part

(sensation, intensity) and an affective part (pleasure, comfort), which are independent of each other. While the descriptive part remains unchanged, the affective part depends on the ability of a stimulus to help the body to return to its ‘normal’ thermal state [175–177]. Both these parts can be important for the decision making process. They are processed in different parts of the brain [178] and are processed simultaneously [179]. Being processed in different parts of the brain leads to the advantage that while a certain sensation (warmth or coolth) may not be pleasurable for the being at the very instant, there is significant advantage in remembering what the stimulus is, especially if it may be used later [178], e.g., warm/cool parts of a residence.

Any departure of the body’s thermal state from the normal state (set-points) leads to a load-error [180]. The preferred thermal sensation depends on mean skin temperature and core temperature [181] and is illustrated in Fig. 6. As an example, the comfort and warmth perception of warm, hand-held electronic devices differs with the ambient conditions [182]. Positive alliesthesia is only possible under conditions of a load-error [110]. Stimuli that help the body towards its normal thermal state arouse a positive alliesthesia and vice-versa. Greater load-errors lead to greater sense of alliesthesia too. In the built-environment, alliesthesia is not limited to thermal pleasure alone and has also been reported for visual stimuli [183,184].

While the concept of alliesthesia has yet to provide some mathematical model for predicting comfort zones, it is a concept that has been validated in multifarious manners. Alliesthesia helps explain certain aspects of comfort under transient conditions, like the anticipatory effect on sensation and comfort following moving from one set of thermal conditions to another (Section 3.1.2). It also provides pointers regarding indoor conditions and operational strategy that can be more comfortable to occupants, like the corrective drift from HVAC systems, discussed in Section 3.1.3. Pleasure perception could be utilised as a ‘common currency’ for evaluating the likelihood of a certain behaviour. When faced with conflicting motivations, such as a combination of behaviours, one of which causes pleasure and the other displeasure, an assessment of net pleasure involving addition, prioritisation, and trade-off, could be used to figure out the direction of spontaneous human behaviour [185]. This can serve as an important aspect of occupant behaviour models. Alliesthesia may be considered as an important part of the link between human psychology and the thermal comfort perception in temporal and spatial transients (Fig. 1).

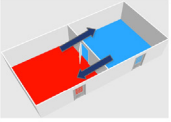































Nature of variation	Certain inferences
Spatial transients 	Subjective ratings lead physiological responses [48,74,75] and stabilize faster [63,72,74,75] Overshoots more pronounced during warm to cool step transient [48,63,71,72,76–80] Comfort ratings have a greater overshoot than sensation ratings [64] Step changes of $\pm 3^\circ\text{C}$ from occupied to transition spaces acceptable [72,81,90,91]
Cycles and drifts 	Cycles of higher frequency/faster changes have lower tolerable temperature amplitude [44,104] Drift rates of 0.5 K/hour from 25 °C do not get noticed by occupants over 4 hours [87]. However, 0.6 K/hour starts to get attention over 4 hours [101] PMV model may be used during up and down ramps of 1.2–2 K/hour [100, 102] Impact of temperature ramps on productivity and cognitive performance imperceptible [102, 103,107]
Non uniformities 	Solar radiation through windows may be used to compensate for air temperatures up to 1.5 K below neutral [136] Least comfortable local body part influences overall comfort and thermal sensation the most [63,138,147,148] Most sensitive body parts [63, 138, 147, 148]: neutral condition - head, face, breathing zone, abdomen, chest and back warm condition - head cool condition - hands and legs

Fig. 5. Summarizing certain observations regarding thermal comfort in heterogeneous environments.

Mean skin temperature	Core temperature	Most pleasant thermal sensation
		
		
		
		
		
		
		
		
		

Legend

 Falling

 Rising


 Holds constant

Fig. 6. Preferred thermal sensation, dependent upon body conditions (adapted from Attia [181]).

3.4. Thermal heterogeneity and occupant well being

Thermoregulation in human beings does not have a dedicated organ, except for may be the sweat glands [180,181]. It relies on a combination of several organ systems — like the cardiovascular system, the nervous system — and human behaviour. Since it brings together multiple organ systems, thermoregulation could have a more important role to play in human health than has been considered for now. The sympathetic nervous system oversees the major processes associated with thermoregulation. It is logical that sensation of comfort or discomfort should have a strong correlation with sympathetic activity, which, in turn, is indicated by HRV [186,187]. Liu et al. [186] found that HRV was significantly raised under discomfort conditions, compared to comfort conditions, even when thermal sensation remained the same.

Occupants get acclimatized to the indoor environments they spend time in and this gets expressed in their behaviour as well as psychological perception. People who are used-to mechanical cooling have weaker thermal adaptability as compared to their counterparts used to naturally conditioned spaces [188]. Lack of need for regulatory responses, in a conditioned environment, could in fact end up atrophying out parts of the multiple systems involved. Occupants unaccustomed to indoor heating systems can be less uncomfortable, and have a higher mean skin temperature, than those used to indoor heating, under mildly cool conditions [82,189]. Individuals from warm humid regions of the world, who are more used to indoor fans, could be better adapted to higher air velocities than those from temperate regions, resulting in higher allowable comfort temperatures with higher air velocity [190]. Such differences brought on by specific indoor environmental settings become important considerations during extreme weather events, especially for vulnerable populations, like the elderly [191].

A few recent studies have shown evidence of “physical warmth contributing to social warmth”, i.e., positively impacting emotional status [192–194]. *In vitro* studies show that the heat shock proteins, generated due to exposure to mild heat stress, can protect cellular proteins and reduce the impact of ageing on cells [195]. Ageing reduces production of heat shock proteins and weakens the ability of the body to respond to heat stress [195]. Acclimation to cold can help obese people and diabetics [196].

Circadian rhythm is observed in multiple organ systems,

controlled by a central biological clock, and plays an important role in synchronizing our body with the changing ambient and preserving health of certain organ systems [197,198]. A reasonable hypothesis is that any event that helps to reinforce the circadian rhythm — e.g. varying air-conditioning set point over an office day — could have positive health implications and studies are required in this direction. This is especially so for the elderly, in whom, circadian rhythm of body temperature may have decreased stability [68,120]. It is hoped that future works will garner better understanding of how flexible indoor thermal environment may contribute to better occupant satisfaction and well being, along with low energy buildings.

4. Measures for personalised comfort

Conditioning a personal space makes sense since the actual occupied space in most rooms is much smaller than room's total volume. Alhashme and Ashgriz [199] used CFD simulations to show that evaluating local temperature close to the occupants can reduce energy consumption, improve thermal comfort and reduce system instability. Using localized systems, the per person energy requirement can be reduced and occupant comfort perception and system response time can be improved [200,201]. Local changes in air temperature and air velocity can significantly impact overall thermal perceptions — in a scale similar to that of overall environmental controls [91]. Personalised comfort systems (PCS), such as a variety of fans and some small heaters, are currently easily available to the consumer. Wyon [202] concluded that providing personalised control of ± 3 °C around the neutral condition can improve occupant average performance.

Personalised ventilation systems and cooling air jets can reduce required ventilation rates [203], curtail cross-contamination risk in high density occupancy [204], improve task response speed, self-evaluated performance, ameliorate frustration and tiredness, and positively influence thermal comfort and air quality perception [55], reduce fatigue and SBS symptoms [205]. As a means of reducing temperature and increasing ventilation, opening windows also provides a fast and effective option [206].

Human body has attraction for variations of certain frequencies, as discussed in Section 3.2.5. Oscillating fans or pulsating radiant heaters can provide impulses of such frequency to improve comfort

Table 3
Corrective power of different PCS.

Cooling solutions	
System	CP (°C)
Uncontrolled air movement	≥−3.5
Frontal cooling jets	−2 to −4
Ceiling fans	−4 to −7
Chair cooling	−2 to −5
Warming solutions	
System	CP (°C)
Chair heating	+7 to +10
Foot/hand warmers	+2 to +10

[63,207]. Ceiling fans, and other such stationary fans used in room often also have a significant variability in the air velocity they impart and this may be partly the cause behind the occupant satisfaction they can ensure without being disturbing [47,207]. It would be interesting to investigate the impact of incorporating such frequency into the operation of personal/local comfort systems.

Different localized cooling devices, whether convection or radiation based, have been found to deliver similar levels of occupant thermal acceptability [205]. Zhang et al. [14], in their review of PCSs, defined the term corrective power (CP) as the “difference between two ambient temperatures at which equal thermal sensation is achieved”, with and without use of PCS. They also noted that use of PCS consistently lead to better occupant satisfaction and that sensation values corrected more than comfort values — except for may be transient conditions. Corrective powers of PCSs, as reviewed by Vesely and Zeiler [208] was 4–5 °C for both cooling and warming solutions. Corrective powers of different systems, as summarised by Zhang et al. [14], is given in Table 3.

Estimated energy savings for cooling CP of 2.5–6 °C is 4–51% and for heating CP of 2.5–3 °C is ~17% even accounting for the energy consumption of personalised or localized alternatives employed [208]. Schiavon and Melikov [209] stressed on the importance of power consumption of personalised cooling systems (with focus on fans) for achieving a net positive energy conservation. The best cooling effect per unit of power expended may be provided by desktop fans [210], and certain high efficiency fans currently in market consume just 17.5 W at their top speed setting [49].

Taking of food or drinks is a ‘non-gadget’ means of personal control. Consuming hot or cool food items/drinks can have a considerable impact on body temperature, especially as the impact on core temperature can be direct. Digesting food increases metabolism to an extent such that core temperature can rise by ~0.01 °C per ~160 kcal of food consumed [68]. This is apart from the effect of the food's own temperature. Consuming an ice cream or a can of cold-drink can have an average cooling effect of ~12–14 W over an hour and a portion of soup could have a warming effect of ~13 W over an hour [125,211]. For a person engaged in standard office activity, this could mean nearly 10% of their metabolic rate. It has been reported that ingestion cool food/drink in intermittent steps can have better efficacy than one time bulk consumption [212]. Further, consumption of cool drinking water has also been shown to abate the impact of hot weather on psychological performance [213]. As conditions get warmer/cooler, occupants may increase their consumption rate of such food/drinks to retain their comfort levels [125].

4.1. Availability of occupant controls

Availability of occupant control forms an intricate linkage

between personalised comfort systems and human psychology — as illustrated in Fig. 1. Because of the sheer variety of occupant preference and perception, personalised control over the indoor environment should help improve satisfaction of the majority of occupants [7,214]. Control options improve thermal comfort, visual comfort, overall satisfaction, productivity, and can even reduce incidences of SBS/building related illness symptoms in offices [82,215–218]. With occupant control, Standard 55 lifts any upper limit on indoor air velocity (Section 2.5) and relaxes considerations of temperature drifts (Section 2.2). Environments where occupants believe they have more control, have better comfort ratings under similar temperatures — homes better than offices and offices better than climatic chambers [126]. Occupants in charge of their own heating needs have a lower neutral temperature and a warmer sensation at similar indoor temperature, than occupants experiencing district heating [219,220]. Just the awareness of having control options/adaptive avenues, can aid psychological adaptation [44] and improve satisfaction [82,126,221–223]. Contrary to this, people unaware of personalised measures can be less comfortable than those aware of such measures [97].

Adjustments at a personal level — to clothing, to met rate, or just accepting the condition — is often preferred by office occupants over adjusting the thermostat, even when such an option is available [214]. This could be due to the need to adjust to one's co-occupants. Occupants working in office environments with flexible desk arrangements have been found to be more satisfied with the perceived thermal comfort and air quality, possibly due to the option of seating location being available to them [224].

Boerstra et al. [225] explored the aspect of control over desktop fans. Occupants did not distinguish between two sets of conditions, involving the fan being under their control or fan being pre-set at their preferred value but without any control, in terms of comfort perception or intensity of SBS symptoms. Fans being operated without control gave improvement in task performance though preference of occupants was for the condition where they had the control. A suitable compromise could be that fans are started off at a group average preferred velocity, without occupants needing to start them. The occupants are informed that they can control the speed if they feel the necessity.

Herbert Simon conceived the term ‘Satisficing’ to explain an economic practice of “adequately meeting perceived needs without going to extremes” [4]. As explained by Leaman and Bordass [4], occupants are satisficers, who desire simple, clearly explained systems, that take into consideration their feedback and respond fast to an occupant action. Occupants desire just an optimum level of control over their environment. Too many buttons to push and too many options can make the environment look less under control and more chaotic [222]. Occupants do not want to actually maintain the environment. That, they would normally feel, is the building management system's (BMS) job. People who are frequently having to resort to environmental controls may be the most dissatisfied with the thermal environment's state [226]. But they do want the idea of control — to be used when BMS is not functioning properly or some discomfort turns up. It could be most beneficial to have the automated building systems playing the role of an observer, who allows for manual manipulations but also has the capability of set-back, in small steps. Because, often users do not have an incentive to change the settings once their cause of discomfort has been eliminated by a previous action. While providing occupants with personalised systems, it also makes sense to have some form of communication between these personal systems and the overall conditioning system of the building. This would let the two mechanisms work in synergy, towards improving comfort and saving energy, instead of working against each other and increasing energy needs.

4.2. Individual differences

One of the arguments in favour of personalised thermal comfort arrangements is the wide variations in individual physiology. Oral, rectal, tympanic, and mean skin temperature can vary by as much as 5, 0.8, 2, and 1 °C, respectively, across individuals [227,228]. And the source of these differences is more likely to be inter-individual differences than age or ambient conditions [229]. The influential individual parameters are: fat mass, body surface area (BSA) to body mass ratio, maxVO₂ consumption, sweat rates, and heart rate [228,230]. On the other hand, personalised measures, like local warming, have been shown to have a consistent effect on improving comfort, across age and gender groups [231].

It is a common observation that the ability to thermoregulate reduces with age and reduced fitness; increase of illness and disabilities may be an important reason for this [191,232]. The elderly have reduced responses in terms of sweat output, skin blood flow, and cardiac output volume to heat stress [233–235], reduced muscle mass and oxygen consumption, leading to lowering of basal metabolic rate (BMR) [68], thermoreceptor sensitivity [69], and compromised ability to discriminate temperature sensations [236].

If the effects of fitness level, body compositions, and chronic diseases are accounted for, it would seem that heat tolerance is minimally affected by just the chronological age [191,235]. The enfeebling of cold defences (like vasoconstriction and thermogenesis) are linked with age directly and the decline is observed even when physical fitness has not been impacted [99,191,236,237]. Reduced functionality of autonomic thermoregulation in face of cold exposure may lead the elderly to rely more on behavioural defences, like, seeking higher heating set points [238]. Such behaviour may account for higher heating energy consumption in residences elderly residents [239].

In terms of physiological differences, women have lower body mass, lower BSA, a lower BMR/BSA ratio and higher BSA/body mass ratio (implying a lower heat generation to heat loss surface area ratio), thicker subcutaneous fat, a slightly higher normal temperature, higher sweating and vasomotion thresholds, lower sweat rates, a higher core set-point during luteal phase, greater insulation when vasoconstricted, and lower exercise capacity [112,161,232,240–245]. In warmer and more humid environments, female subjects prefer higher air velocity than their male counterparts [41]. Most studies, done across buildings and laboratories, find women to be more dissatisfied than men with the same thermal environment [244,246,247]. Females prefer higher room temperatures, by about 1.2–3 °C [9,245,246,248,249].

Among a population of office workers, up to 9% could have neutral temperatures differing by 2 °C from the mean value and about 40% could have differences of 1 °C [200]. Wang et al. [140] found that for the same thermal sensation, the finger temperature of individuals could differ by as much as 10 °C. Preferred air velocities of individuals also vary greatly [41,250]. A host of differences exist between individuals regarding perception of a thermal environment. Individual differences tend to significantly impact how common thermal environments are perceived by different persons. These differences continue to be a major argument in favour of more personalised thermal comfort design for indoors.

4.3. Face cooling

The human brain is more vulnerable to damage from rising temperatures than any other core organ [137]. Face sweating was maintained even for dehydrated individuals so that the induced cooling can maintain brain temperature below oesophageal temperature, (i.e., deep body temperature) [251]. Under slightly warm conditions, facial cooling is a welcome relief while facial warming is

perceived as a distress [91,137]. The preference for a cooler brain may be used to justify the advantage of personalised comfort measures focusing on the face, like face fanning [252] and face cooling during exercise [253–255]. By cooling just the face/head, the upper limit of comfort temperature can be pushed to 30 °C [256] and exercise work rate and duration can be improved [144]. The preference for a cool brain can be used to explain why cool ceiling asymmetry can be much more than cool floor asymmetry (Section 2.2).

There is some evidence that heat loss from upper respiratory tract can affect intra-cranial temperature of humans [257]. This may explain why warming of the breathing zone is not appreciated by participants of tests while slight cooling is preferred during transient conditions [62,63]. By same logic, excessive cooling of breathing zone must also be avoided.

4.4. Alliesthesia and personalised comfort measures

It has been long held that load-error for positive alliesthesia can only be due to changes in overall body temperature (to which core temperature is the major contributor) [258]. Some recent works show that small variations in skin temperature and localized thermal stimuli can generate enough load-error for positive alliesthesia sensation [110,111,259,260] while the body, overall, is still within its thermoneutral zone. As certain behavioural regulatory mechanisms can have a feed forward control associated with them [261], further studies may reveal that the peripheral regions of the thermal comfort zone also hold potential for alliesthesial relief. The successful implementations of such alliesthesial measure in actual buildings is contingent upon widespread application of personalised systems [110].

Local means for ensuring comfort can successfully push the boundaries of conventional comfort zones while contributing positively to the thermal and comfort sensation. Imagining the temperature set-points for indoors on a 'comfort line', the conventional comfort set-points and the extensions allowed in lieu of clothing adjustments, local air velocity, local heating etc., are presented in Fig. 7.

5. Impact of other senses

As thermoregulation relies on inputs and actions from a variety of organs and organ systems, thermal comfort perceptions are also affected by environmental factors other than those purely thermal in nature. The intertwined nature of human psychology and physiology and thermal comfort perception is also highlighted as part of Fig. 1.

The most important factor in IEQ perception is not consistent across situations and is often the parameter with which occupants are most dissatisfied [215,262,263]. Studies show indoor thermal comfort being given more importance by occupants, exerting greater impact on overall satisfaction [215,262], and being the most complained about element in indoor environment [4]. Occupants may express their discontent on other factors in terms of the thermal environment, as temperature is a factor easier to complain about and seems easiest to address [216].

Air quality perceived by occupants has a closer relation with thermal comfort rather than the temperature in itself; if air movement adjustments are helping maintain thermal comfort, air quality is likely to be deemed acceptable [43]. Zhang et al. [43], from analysis of the RP-884 database, found that for air temperature between 18 and 25 °C, air quality perception is invariant and drops sharply as air temperatures increase above 28 °C. But, increasing air velocity improved the perception of air quality at 28–30 °C back to the levels at 25 °C. Thus, the increased air velocity

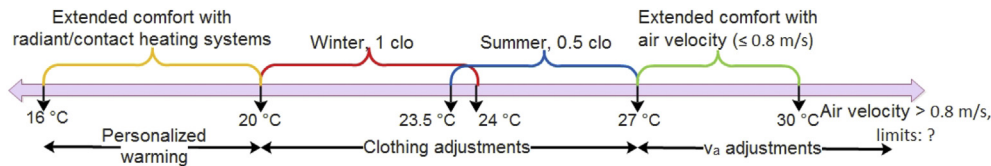


Fig. 7. A broader 'comfort line', reinforced with personal measures to extend satisfaction.

limits proposed by thermal comfort standards (Section 2.5), have a greater role to play beyond just thermal comfort aspects.

Investigation into impact of indoor CO₂ levels on thermal perception showed that while participants may feel slightly warmer as CO₂ levels built up, the difference was not statistically significant [264]. Some studies do show that high levels of CO₂ in itself may not impact air quality perception as much as other pollutants, of which a high CO₂ concentration may be indicative of [265,266]. Lower temperatures have been found to improve the impression of air quality, leading to lower ventilation rates being used in combination with low indoor temperatures [7]. Spending long durations in air conditioned buildings has shown a direct correlation with SBS symptoms [44]. The perceived improvement in air quality due to air movement may either be caused due to an association of moving air with ventilation and natural wind or because the air stream disrupts human body's thermal plume, improving air quality around the breathing zone [250,267].

Temperature perception in a space does have a direct relation with the glare sensation [268]. Studies on effect of lighting colour on thermal comfort have often ended with ambiguous results [269,270]. The red end of the spectrum does seem to evoke warmer responses, as compared to the bluish spectra [269,270]. Fanger et al. [271] found that difference in noise level did not significantly impact preferred temperature of subjects, while use of an extreme wavelength of red light lowered the ambient temperature preference by 0.4 °C. Light spectra may have a definitive impact on thermoregulation and visual perception, thus impacting thermal sensation and comfort and occupant clothing preferences [269,270]. Lighting intensity may even have an impact on vasoconstriction in upper limbs [272].

There is some evidence that visual sensory input — in terms of images/videos of warm or cold places — can impact thermoregulatory behaviour, for example, impeding vasoconstriction in a cool ambient [273]. Replacing a 'cold décor' (white walls, bare lighting, rubber matted floors, wooden chairs) with a 'warm décor' (red carpet, wooden panelling on wall, deflectors for fluorescent tubes, etc.) can have an effect equivalent to raising temperature by 1.4 °C on subjective perception though objective values (body temperature) may not differ [274]. Such findings point to the importance of occupant psychology in designing for thermal comfort.

Studies dealing with the interaction between thermal, aural, and air pollution perceptions showed that around 26 °C, changes of 3.8–7 dB(A) in sound level or 7 decipol in air pollution level or 0.5 m² in window area were similar to a change in temperature of 1 °C [7]. Combination of noise and warm temperatures do not affect physiological responses though aural discomfort can impact thermal comfort under warm conditions [275]. For women, thermal comfort is more important than aural comfort and they can be accepting of noisier environments than men [275]. Findings do suggest that people are more accepting of natural sounds than urban noise [5]. Also, occupants in naturally ventilated buildings may have adapted themselves to such prevalent level of noise that is more than the allowed levels in standards for AC buildings [276].

Thermal comfort and acoustic comfort can clash in terms of ventilation noises and noise absorbing materials that reduce exposed thermal mass, impacting ability of building thermal mass

to moderate thermal environment [268,277,278]. An odour that is imperceptible in a cool dry environment can turn into a major irritant as thermal environment is moved towards the upper limits of comfort zone [262]. Source elimination of pollutants thus becomes more important in buildings that strive to exploit the entire breadth of comfort zones.

There are two aspects to the IEQ parameters of a building that may be useful for lowering energy usage in conditioning buildings. One is that the input to different senses may be used to provide small but additive contributions to comfort, especially in transitory spaces. The other is elimination of any sources of stress that occupants may unduly ascribe to thermal environment. Both aspects should be useful in designing more energy efficient, yet comfortable buildings. And both aspects definitely require further coordinated, cross-disciplinary investigations.

6. A summary

Fig. 8 attempts a graphical summation of the dynamic aspects of indoor environment we have discussed: step changes, non-uniformities, drifts and cycles, and local control. Under each aspect, certain noteworthy works related to the topic are listed, including some seminal works like: de Dear et al. [70], Gagge et al. [77], Berglund and Gonzalez [86].

For each aspect, we also make some subjective comments regarding the current state of investigations into the field, put in terms of 'Strengths' and 'Deficiencies'. A growing trend is noted in making the investigations detailed in terms of measuring and recording objective environmental parameters, subjective response, and physiological values. A common shortcoming is that almost every study has been conducted in laboratory environment. It is quite evident why this is the case. Taking measurements regarding thermal environment heterogeneity in the uncontrolled field environment is an onerous task. Due to this deficiency though, there always remains the doubt as to how well the results will translate to actual use. The solution could either be field studies with certain simplifying assumptions and detailed instrumentation, or it could be use of complicated climate chamber systems that very nearly replicate actual indoors.

Certain aspects of human physiology and occupant psychology were discussed to lend credence to subjective response of occupants, to put forth the idea that there is often a fundamental reason behind why cooler heads and warmer toes are preferred, why transitions can induce stronger sensations than in steady state etc. Regrettably, as of date, most buildings do not put to use even the full width of comfort zone advocated by Standard 55, much less go further towards flexible and variable thermal environment. Less rigorous control, more personal autonomy, and a more responsive indoor environment would improve occupant experience of indoors while avoiding splurging on energy. Accordingly designing buildings and innovating solutions for occupant comfort that are effective, energy efficient, and address the prevalent issues among occupants, are the need of the hour. Measures aiming to reduce building energy consumption without concerning themselves with occupant health, comfort, and performance are sure to fail. It would be a blunder to assume that energy conservation and productivity





Aspect of variation in thermal environment	Certain noteworthy works	Comments on the reviewed studies	
		Strengths	Deficiencies
Step changes 	Tsutsumi et al. [34], Dear et al. [71], Chun and Tamura [73], Gagge et al. [78], Horikoshi and Fukaya [88], Goto et al. [94]	<ul style="list-style-type: none"> Detailed objective, physiological, and subjective investigations Wide range of steps investigated 	<ul style="list-style-type: none"> Few studies in field environment Few studies on metabolic steps
Non-uniformities 	Arens et al. [64], Fanger et al. [131], Huizenga et al. [140]	<ul style="list-style-type: none"> Detailed objective, physiological, and subjective investigations Localised comfort measures investigated 	<ul style="list-style-type: none"> Few studies in field environment Mostly simulates an office environment
Drifts & cycles 	Berglund and Gonzalez [87], Kolarik et al. [102], Rohles et al. [104]	<ul style="list-style-type: none"> Long duration drifts investigated Effect on performance investigated 	<ul style="list-style-type: none"> Few studies in field environment Mostly simulates an office environment
Personalised measures and occupant control 	Arens et al. [42], Schiavon and Melikov [210], Luo et al. [221], Boerstra et al. [226]	<ul style="list-style-type: none"> Well-designed studies, use of control groups Effect on performance investigated 	<ul style="list-style-type: none"> Few studies in field environment Lack of studies with automated control+occupant override

Fig. 8. A summary of the different aspects of thermal environment heterogeneity discussed.

are at logger heads. This review suggests that they are more likely meant to exist symbiotically. In the next subsections, we discuss a future prospect and a challenge.

6.1. Global environmental change

With global climate change a looming reality, designing low energy buildings needs to consider capricious climate variations at play. In a warming world, heating energy demands should reduce while cooling energy demands rise. But the rise is more than likely to offset the reductions [49,279,280]. Buildings designed or retro-fitted for a cold winter and a mild summer will have rising complaints of overheating as the summer becomes more warm than mild [281,282]. Designing buildings as well as operational systems that can account for such vagaries, will be a challenge.

By 2030, 85% of world population is expected to be located in developing countries [9], i.e., mostly in the currently warm/hot parts of the globe. Though indigenes of the tropics do have a significant level of acclimatization to their climate, how much can this really help them in a warming globe? What is anticipated is that with economic growth, occupant expectations from indoor environments would rise [239], leading these countries to contribute the most to rising cooling demands. How to influence comfort criteria and building design and operation for such countries so that occupant satisfaction can be ensured while avoiding buildings becoming ‘cold domains’ closed off from nature is an imminent challenge for the future.

6.2. A rising trend for green buildings

Post occupancy evaluation in a variety of “Green Buildings” — near ZEB, ZEB, passive houses, low energy houses etc. — and in different countries across Asia, Australia, Europe, and North America, show good overall occupant satisfaction [283–288]. As an overall inference, it may be stated that low energy buildings have achieved a definite level of penetration into society and in their turn have not failed the test of human acceptance. The hope, going further, is that better understanding of human thermal comfort requirements, can assist and drive the progress of comfortable buildings, with better occupant satisfaction and yet lower energy consumption. Our discussions show the potential for creating an indoor environment with greater diversity in its character, that could enhance subjective acceptance of occupants and help save

energy. There are also aspects of differences in individual physiology which would advocate for more personalised environments and more personal control to extend the realm of thermal comfort to all.

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