Title
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Expectations of indoor climate control

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Abstract

This paper discusses reassessment of indoor climate control in the context of current thermal comfort practice and research. We review the limitations of comfort models and standards with several examples. We examine how people's thermal sensation and preference may be influenced by culture and climate and associated issues of thermal expectations and adaptation. Finally, we discuss how incorporating these factors into future comfort standards might yield more 'effective' indoor climate control.

Keywords: Climate control; Thermal comfort; Adaptation; Modelling; Expectation

Mahdavi and Kumar [1] present a well-stated argument that indoor climate control should be reassessed as we approach the next millennium. We share many of their concerns, particularly about the environmental impact of current indoor climate control practice. The earth's energy resources are dwindling, and fuels used for heating and cooling buildings constitute a large fraction of total consumption (for the US, 30% of the total in 1992). Building energy use therefore has a significant impact on environmental concerns such as global climate change, nuclear waste and acid rain. Recent scientific consensus that this planet has indeed experienced global warming beyond the normally expected random variability, and that these trends directly result from anthropogenic greenhouse gases emitted into the global atmosphere [2], reinforces the timeliness of the critical appraisal of Mahdavi and Kumar of how we manage indoor climates.

There is a pressing need to re-evaluate the issues raised or alluded to by Mahdavi and Kumar [1] ('M&K' throughout this paper). First, why do we condition our buildings in the manner we do, with centralized HVAC systems providing static, uniform environments? Second, what do people expect of comfort standards, and how realistic are those expectations considering the limitations of current practice and research? Finally, how can comfort research and standards development get beyond the 'single-temperature setpoint' paradigm? M&K begin to address these topics, but we were disappointed to note that much of the past and current research in this field is disregarded in their arguments. In addition, they fail to suggest any clear future research directions. It is only through scientific analysis of carefully considered questions that the issues will be resolved. This paper gives our perspective on these issues, and suggests areas where we will need to generate knowledge before we can implement changes in how buildings are conditioned.

We would like to begin by pointing out that the indoor climates measured in field studies of office environments demonstrate that air-conditioned buildings are typically controlled within temperature ranges that are a narrow subset of the range allowed by ASHRAE Standard 55 [3]. ASHRAE 55 specifies a range of 6°C (20–26°C ET* or 68–79°F ET*), from the bottom of the winter zone to the top of the summer zone; 3°C for each season. This is much larger than the actual operational ranges measured in field studies of climate-controlled buildings worldwide [4–6] (M&K's refs. [31,32,33]). These measurements show a standard deviation of 1–1.5°C with a seasonal shift of 0.5–1°C, centered around 23°C. If we use Lovins' [7] approximation for the amount of cooling energy saved by allowing buildings to float one additional °C, allowing buildings to float across the entire warm side of the ASHRAE 55 comfort zone would alone reduce cooling energy consumption by 5% or more.

Why are buildings controlled within such a narrow range? Because allowing the temperature to vary even within the range allowed by standards results in increased discomfort for some part of the population due to people's expectations and their culturally-induced clothing norms. For example, let us assume that a female sits at her desk with bare legs in a skirt because the corporate dress code or current fashion dic-

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tates it — yet she shares the same thermal zone with a male colleague in a business suit. A PMV-based [8] analysis will indicate that there is no single temperature at which both will be satisfied. Indeed, assuming all else to be equal, their wardrobe decisions would give a 3°C offset in their preferred temperatures. In the absence of individual temperature control, the compromise in the US has been to control to a constant temperature based on an average clothing value. If clo = 0.7 (ASHRAE 55, winter/summer average), met = 1.2 (typical office), PMV = 0 implies air temperature = 24.1°C (74.1°F). For this example though, the female will likely be too cool and the male will feel too warm, and neither of them will be satisfied.

The above example illustrates a situation in which individual clothing variation can amplify the number of people dissatisfied with a fixed thermal environment. However, taking a different perspective, one might reasonably suggest that people ought to vary their clothing to suit their individual thermal needs, so that clothing differences become a mechanism by which individuals' differences can successfully be accommodated by a single zonal temperature. In fact we do see instances of this type of local fine-tuning but they are usually restricted to the extremes of measured indoor climates, not near the center of the comfort zone where most US buildings are controlled. We have found two different explanations for this. The first is related to the effect air-conditioning has on people's expectations. Anecdotal evidence from our field studies in offices suggests a very real reluctance on the part of many workers to take responsibility for any thermoregulation. They adopt an attitude of ''that's what the air-conditioning is supposed to do for you, isn't it?'', and absolve themselves of any responsibility to thermoregulate, physiologically or behaviorally. This reflects a perhaps unrealistic expectation of the ability of centralized air-conditioning to satisfy all people. The second explanation is related to corporate dress codes. The 'executive' is often expected to dress in a multi-layer wool suit whether it has a skirt (female) or pants (male), regardless of the outdoor climate. Persons lower in the workplace hierarchy are not necessarily expected to dress as rigidly and this results in a 'pecking-order' of clothing insulation that mirrors the power structure within the workplace. Our collective field research across four continents indicates that this arrangement guarantees widespread thermal discomfort, even when the physical environmental conditions meet current thermal comfort standards. What is it that compels a banker sitting in his/her office on the 63rd floor of the corporate headquarters in Hong Kong to wear a three-piece suit in the middle of a hot-humid summer or the banker he/she is talking to via satellite sitting in San Francisco in similar clothing on the 63rd floor of a sealed building in a temperate climate that begs for natural ventilation? We suggest that the reason is a dress code that confers local/national/international 'credibility' and that this dress code overrides rational thermoregulatory behavior. The building industry faces a very difficult challenge in trying to thermally satisfy a large percentage of the office population. High levels of dissatisfaction in air-conditioned office buildings have little to do with current research methods, may only be tangentially related to comfort standards, and have much more to do with expectations and cultural/clothing norms.

A second question raised by M&K's paper is: what do the building industry (as providers of environments) and office occupants (as consumers of that product) expect from thermal comfort standards, and how realistic are those expectations in light of the limitations of existing research? Do critics embrace an (unreasonable) expectation that, if the standards are met, then *all* of the people should feel thermally comfortable in *all* buildings, *all* of the time, in *all* climates? Conditions prescribed in the standards are driven by thermal comfort models that predict thermal sensations, and by assumptions about which of those thermal sensations will be deemed acceptable. The models are derived from extensive and reproducible laboratory experiments on groups of people, and the sensation predictions represent group mean responses. The fact is that existing thermal comfort models, such as Fanger's PMV [8] or the two-node model of Gagge et al. [9], were never intended to predict the thermal responses of a specific individual on any given day. Their predictions should be interpreted as what a hypothetical 'average' person will feel, or as the average response of a large group of people experiencing the same conditions. Individual differences between people are frequently greater than one scale value (on a seven-point thermal sensation scale) when both people are exposed to the same environment (inter-individual variance). In addition, how a person feels in the same environment from day-to-day can also vary on the order of one scale value (intra-individual variance). One scale value corresponds to approximately 3°C, which is the full width of the comfort zone (in either summer or winter). It is simply not possible to predict exactly how an individual is going to feel on one particular day using PMV or other currently available models. That is the reason the comfort zone is as wide as it is, and why it is unreasonable to expect *all* people to be satisfied within a centrally controlled environment, even when the thermal conditions meet current standards.

Finally, we would like to examine how HVAC practice, thermal comfort research, and comfort standards development can get beyond the single-temperature setpoint paradigm. Cognizant of the levels of dissatisfaction with the thermal environments in office buildings, and the limitations of current HVAC practice, there is broad agreement among thermal comfort researchers that individual control of local thermal environments is by far the best solution from a comfort and satisfaction standpoint. If individual control were provided to workplace occupants, the need for prescriptive standards would be eliminated — a design guide that defines the necessary range of operation of individually-controlled 'task conditioning' devices is all that would be required [10]. If such solutions were to become universal, current thermal comfort paradigms would become accepted as descriptive of the overall physiological and psychological interaction between buildings and people but not accurately representing the phenomena in detail. In addition to optimizing occupant comfort, task conditioning systems can also lead to reduced energy consumption through the potential for task-defined zoning, intentional stratification, occupancy sensor shutoff of local fans, increased use of economizer cycles resulting from higher return temperatures, increase in chiller efficiency due to higher supply temperatures, and the opportunities for greater temperature drifts and for less rigid control of the ambient space [11,12].

If we are to develop a more accurate understanding of thermal comfort in buildings, we must begin by re-evaluating some of the traditional research methods we use. For example, our comfort standards serve to prescribe acceptable conditions, yet the surveys used in the experiments on which these standards are based never asked about acceptability directly. Instead, thermal comfort research and analysis methods typically incorporate two fundamental assumptions: (i) optimum temperature corresponds to a 'neutral' thermal sensation, and (ii) the notion of 'acceptability' is associated with specific thermal sensations on the ASHRAE 7-point Scale. However, analysis of data from several field studies showed that: (i) neutrality is not necessarily ideal for a significant number of people; (ii) people's preferences for non-neutral (warm or cool) thermal sensations are common, vary asymmetrically around neutrality, and in several cases are influenced by season; (iii) thermal sensations outside of the three central categories of the ASHRAE 7-point Scale do not necessarily reflect discomfort for a substantial proportion of people [13]. These findings suggest that a much richer landscape exists beyond the ASHRAE Standard 55 'comfort zone', and that our research methods need to ask questions about the complexities of thermal preference and acceptability in a way that can be assimilated into a better framework of thermal comfort prediction.

M&K rightly point out that thermal comfort standards, as they are currently written, are too restrictive to allow *fundamental* departures from the status quo of energy intensive, mechanically conditioned buildings. More efficient task-conditioning systems or 'passive' design features such as individual access to windows typically use air movement or radiation to provide the individual's comfort during temperature excursions outside the range prescribed in current standards. So one clear goal of future thermal comfort research should be to provide the information needed to decide whether the scope of current standards legitimately extends beyond centrally controlled air-conditioned buildings. The wording of ASHRAE 55 [3] does not currently restrict the standard's scope — yet the lack of information about non-centrally-controlled environments effectively limits its application. We should bear in mind the empirical bases of the standards; namely climate chamber experiments involving groups of human subjects who have been expressly instructed *not* to undertake any thermoregulatory behaviors such as adjusting clothing, opening windows, etc. Therefore, generalizing from such research findings to more variable environments such as those found within naturally ventilated buildings seems to us to be a little overzealous. A recent literature review of field experiments [14] across various climate zones established that comfort temperatures predicted by comfort models were close to the mark in centrally air-conditioned buildings, regardless of climate zone, ethnic composition of sample, gender, acclimatization, age, etc. However, in naturally ventilated buildings, comfort was found across temperatures ranging well beyond those prescribed in the standards such as ASHRAE 55. Because of this, we feel that current standards should have their scope restricted to circumstances in which the occupants have little or no control over their own microclimates. That, after all, was the reason such standards were developed in the first place, at the advent of centralized HVAC technology.

Once the industry openly acknowledges that the application of current thermal comfort standards must be limited to centrally-controlled environments, then the next step is to work towards developing a complementary set of standards that reflect people's adaptive mechanisms, and that can be appropriately applied to buildings incorporating passive strategies or task-conditioning systems.

The most immediate line of inquiry should be into adaptation by behavioral or technological adjustment, where individuals can directly manipulate the heat fluxes that govern their overall thermal balance. 'Behavioral' implies that a person adjusts to the surroundings by changing his or her personal variables, such as clothing. 'Technological' refers to adjusting the surroundings to directly affect the environmental variables (temperature, humidity, air velocity, radiant temperature). Examples of these adjustments would be turning on a fan, blocking an air diffuser, or opening a window or a curtain. The effects of such adjustments can be determined in both laboratory and field experiments [15,16].

The type of adaptation most thoroughly documented in the scientific literature is physiological acclimatization. Acclimatization is defined as changes in a person's physiological thermoregulation setpoints (e.g. the onset of sweating) that result from prolonged exposure to climatic conditions outside the traditional comfort zone. But there is also a third form of adaptation that is psychological in nature, relating to people's changed expectation. This is analogous to the concept of habituation in psychophysics, and occurs when a person's individual 'comfort setpoints' (or preferred temperature) track the cycles and variations in indoor climates, which in turn may follow the diurnal or seasonal outdoor climate patterns, or indeed, longer-term climatic changes. After repeated exposure to variation in environmental conditions, a person's expectations of those conditions may become more relaxed — even anticipatory of temporal changes. This is, most likely, the explanation behind the differences found in the preferred temperatures of people in air-conditioned versus naturally ventilation buildings.

Our challenge as researchers is to understand these various adaptive mechanisms, develop mathematical predictive models where possible, and eventually incorporate those models into 'responsive' standards that acknowledge the richness of human–environmental interactions and the potential for less energy-intensive design. Future 'responsive' comfort standards could initially be formulated to complement existing standards based on heat balance models. Static heat balance models already account for short-term physiological adaptations, such as sweating and shivering, but could eventually be supplemented by empirical equations describing longer-term shifts in, or contextual effects on, thermal expectations. In theory, responsive standards have the ability to incorporate the effects of behavioral or technological adjustments, dynamic profiles of clothing and activity, and climate/building/system/occupant feedback — all of which are currently ignored.

The ability to incorporate expectation into standards is an area where the heat balance models offer no information. The mind has a 'thermal' memory of environments that exists across many timescales — seconds, minutes, hours, days and years. In terms of thermal comfort judgment, how significant is a one minute exposure to artificially-cooled air after a month in the hot-humid tropics? How meaningful is a month spent in the hot-humid tropics as part of years of life in a cold climate where added heat and reduced air movement are the most commonly desired thermal environmental changes? How significant is a lifetime of working in static environments for determining resistance to working in a dynamic environment? These are questions that can be answered by analyzing expectations yet very little has been done to date to investigate this psychological dimension of thermal comfort.

To summarize: comfort is defined [3] as "that condition of the mind that expresses satisfaction with the thermal environment". Comfort is not a physiological condition but a state of mind. The thermal ranges and asymmetries experienced while lying on the beach wearing next to nothing with the wind blowing and the sun beating down would be far beyond those allowed by any indoor comfort standard — yet the person experiencing the beach would not necessarily say he or she is thermally uncomfortable. Would the beach conditions be appropriate inside a building? Probably not, yet the difference lies not in physiology but in expectation. We will come closer to M&K's ideal of 'effective' indoor climate control as we understand how people's thermal sensation and preference may be influenced by culture and climate, and associated issues of thermal expectations and adaptation. We feel that future thermal comfort research should be directed at these broader questions of thermal perception. Barriers to relaxing single-setpoint temperature control are cultural, not rooted in comfort research or standards. ASHRAE Standard 55 [3] is not an obstacle to energy conservation per se, for merely utilizing the full ASHRAE 55 temperature ranges would already result in significant savings. Only by relaxing culturally-induced clothing norms and occupant expectations of rigidly controlled environments can we make significant progress toward indoor climate control strategies that simultaneously enhance comfort, conserve energy, and minimize global environmental impact.

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