Thermal comfort, productivity and energy consumption in the tropical office environment: a critical overview

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ABSTRACT: Thermal comfort has developed along two distinct models: deterministic and adaptive. We investigate the validity of these models against the increasingly urgent call to reduce building energy consumption. The air-conditioned office, predicated on the deterministic thermal comfort model, expends about 50% of its energy on air-conditioning. In a resource-constrained world, while acknowledging the need for thermal comfort, the parameters of thermal comfort should be re-examined. This paper explores the potential for the adaptive thermal comfort model to provide acceptable levels of thermal comfort while reducing cooling demand in office buildings located in the tropics. It links thermal comfort and productivity with the persistence of air-conditioning in knowledge-based economies located in the tropics.

Conference theme: Urban

Keywords: *thermal comfort theories, office productivity, hot-humid tropics*

1. BACKGROUND

The cost of supplying energy to the office space has historically been insignificant compared to the cost of labour. A study on a typical American office (Holz, Hourigan, Sloop, Monkman, & Krarti, 1997) found the cost of salaries 100 times more than that of energy. In Singapore, the electrical consumption of offices account for 12% of the overall non-manufacturing sector's usage, with an average annual energy efficiency of 231 kWh/m^2 (S. E. Lee, 2001). In an ongoing study by the Energy Sustainability Unit in Singapore (http:///www.esu.com.sg) the average building (in the 25th-75th percentile) uses 49% of its energy on air-conditioning and a further 14% on mechanical ventilation.

However, the common modern day office is predicated on an uninterrupted supply of affordable electrical energy. Ubiquitous deep plan buildings with fixed windows and office equipment demand air-conditioning, artificial lighting and power. However, in a resource constrained world where there is an increasing need to reduce our energy footprint, what levels of comfort could we forgo without sacrificing productivity?

2. COMFORT THEORIES

Fanger's seminal work (Fanger, 1970) underlies the standards used both by the International Organization for Standardisation (ISO, 2005) and the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 2004). His climate chamber experiments yielded the PMV (Predicted Mean Vote) formulation that has been widely adopted as the de facto standard for thermal comfort with air-conditioning. For typical office conditions (at RH:50%, v=0.5m/s, 1 met, 1 clo) the neutral temperature is 24.8ºC.

On the other hand, we have the adaptive mode of defining thermal comfort which can be attributed to Aulicem (1969) and extensive field studies by Humphreys and Nicol (M. A Humphreys, 1995; Michael A Humphreys & J Fergus Nicol, 2004; Fergus Nicol, Michael Humphreys, Sykes, & Roaf, 1995; Fergus Nicol & Pagliano, 2007; J. F Nicol & M. A Humphreys, 2009). They found that compound indices failed to predict accurately the comfort temperature for free-running buildings and a simple regression of outdoor temperatures was a far more reliable gauge:

$$T_c=5.41+0.73T_o \qquad (1)$$

Using a typical Singaporean afternoon temperature (T_o) of 30-32ºC would yield a resultant indoor comfort temperature (T_c) of 27.3-28.8ºC (eq. 1), a sensory change (2.7ºC<ΔT<3.2ºC) that can be readily achieved with indoor fans delivering an effective velocity ve=0.5-0.6 m/s (eq. 2, where v_e=v - 0.2 m/s (Szokolay, 2000)).

$$\Delta T = 6 \cdot v_e - 1.6 \cdot v^2 \qquad (2)$$

Would the comfort delivered by a ceiling fan at 32ºC be equivalent to that from an air-conditioner at 24.8ºC? How could there be such a vast difference in comfort expectations between the two modes of cooling? An ASHRAE report (de Dear, Brager, & Cooper, 1997) sums up the debate concisely:

> The former [PMV model] permits only behavioural adjustments (personal/technological) to heat balance variables such as clothing or air velocity, whereas the original adaptive models were premised on changing physiological (i.e. acclimatization) and psychological (i.e. expectations/habituation) setpoints. While this may seem to be a fine distinction, failure to appreciate it has, in the opinion of the authors, been responsible for unnecessary controversy between the two sides of this debate.

The two camps have been irreconcilable and one of the problems has been the semantics of thermal comfort. The deterministic model comfort is predicated on the notion that comfort is the absence of discomfort. PMV is thus intended to discover the neutral zone in the thermal sensation scale, also referred to as the 7-point ASHRAE scale. Adaptive comfort is inclined to the body's acceptance of seasonal fluctuations and considers comfort levels with non-neutral thermal sensation to arrive at the optimum temperature on the Bedford scale, allowing an occupant to indicate one is warm/cool and still comfortable. The debate has polarized thermal comfort studies into the following distinct identities:

Deterministic comfort:

Climate chambers, air-conditioning, equipment-oriented, combined indices, computationally complex, disconnected from nature, universal, institutional.

Adaptive comfort:

Field studies, natural ventilation, building-oriented, air temperature, computationally simple, correlated to natural patterns, individual, personal.

In the course of reviewing the literature of both arguments the gap was quickly apparent: there were very few studies that attempted to bridge the arguments and research methods between the two. For the architect, this debate lies at the core of how we design: should it be a matter of freedom of form and plan with the confidence that the appropriate equipment can solve any comfort requirement, or should the building design resolve the climatic considerations, with low energy equipment like ceiling fans merely augmenting the comfort demands on particularly hot days.

A needful way to resolve this divide would be to compare thermal comfort against thermal sensation conducted by field studies in air-conditioned offices: thus using the tools of adaptive comfort to verify the occupant preference in a centrally controlled environment.

3. RESOLVING COMFORT WITH PRODUCTIVITY

Such a study was undertaken by Schiller who found that despite the universality alluded to by PMV, office workers in air-conditioned offices had an optimum temperature of 22.5ºC, significantly lower than PMV would have predicted at 24.8ºC (Schiller, 1990). The need to distinguish between the Schiller's optimum temperature and Fanger's neutral temperatue was because her surveys allowed occupants to provide feedback not just on the neutral temperature (7-point ASHRAE scale), but also on the level of comfort experienced (6-point general comfort scale). The inclusion of a comfort scale does not only add another dimension to the study, it distinguishes thermal sensation from satisfaction, a view that is shared by Baker (Baker, 1996). Since field studies have been conventionally accepted as more representative of real-world climate control needs, Schiller's observation could be further explained by the increased need for cooling caused by real-world stress, as opposed to the climate chamber experiments where occupants were given tasks that merely simulated work. We postulate that this is the same explanation to the discrepancy found in a study of office occupants in Sydney (Rowe, 2001) where actual mean comfort vote was 0.30 higher than predicted, i.e. occupants would have voted as predicted had $T_{operative}$ been 1.14ºC cooler. A classroom study in the tropics also showed a preference for cool sensations (Wong & Khoo, 2003). This leads us to deduce that occupants are most comfortable when they are slightly cool, not when they are neutral.

If we accept the assumptions that the ideal temperature is likely to be cooler than neutral, and that field studies reveal a greater demand for cooling than climate chamber studies, we can argue that thermal comfort cannot be defined solely in terms of physical activity, but that mental work imposes cooling requirements the body alone would not necessitate. This would be particularly true for office workers, where the rigours of mental concentration can account for a preference for cooler environments. This mental load has not been accounted for in comfort studies, where metabolic load is related to physical and not mental activity. The mental metabolic load could also explain why natural ventilation has never been attractive to offices in developed cities in hot and humid climates: the adaptation to warm (30-32ºC) and humid conditions (RH=60-80%) could come with a penalty in mental performance. Being comfortable in these conditions is not synonymous with being the most productive. Whilst this notion has not been explored in building thermal comfort studies, there is substantial anecdotal evidence in other fields.

Neurons have been studied thermodynamically (Karbowski, 2009) to ascertain that, at an average firing rate of 1.7Hz (in grey matter 700g in mass), the heat generate was about 7W. If we consider that "a stimulated neuron might fire 20 or 30 times a second" (Siegfried, 2001) the contribution of mental metabolism to overall metabolism (met=1.2 or 70W/m^2) is very significant for the typical office worker. Karbowski further noted that the cooling mechanism of our brains was via heat transfer to the blood for the deeper brain regions and via conduction and convection to the environment for regions near the scalp. Akin to the way computer CPU clock speeds are limited to the availability of cooling, the heat rejection requirements from mental exertion might well justify the need for air-conditioning in offices. This differential need is self-evident in the way we dress: a business suit for the body (1 clo to 1.2 clo) and an uncovered head (0 clo).

Coller and Maddock's study on peripheral vasonconstriction (Coller & Maddock, 1934) also offers some useful support for this argument. They found that the temperature of the skin on the arms and legs accounted for the largest response to environmental and metabolic stimulus and so "a major shift of blood to the extremities is therefore to an area sufficiently large to care for wide normal variations." We thus surmise that a thermoregulatory response to heat is for the diversion of blood from the rest of the body, including the brain, to the extremities by dilating the peripheral vessels there, suggesting that heat adaptation could come with a downside to mental performance.

In more extreme conditions, heat stress significantly impairs judgment and performance. Several military studies have been conducted to ascertain its relationship and limits (Manton & Hendy, 1988, to name one). Hancock (Hancock, 1986; Hancock & Vasmatzidis, 2003) demonstrated that shifts to deep body temperature had pronounced effects in the performance of complex tasks (vigilance, tracking and multi-tasking). However conditions that can cause perturbation to deep body temperature fall well beyond the comfort scales into thermally stressful regions not typically encountered in the office. Of interest is the region where there is sensible discomfort without disturbing deep body temperature: a region where Hancock found no performance deterioration in his laboratory-based subjects.

Humphreys and Nicol, earlier noted for their work in adaptive theory, undertook a field study to determine how comfort affected productivity (Michael A Humphreys & J. Fergus Nicol, 2007). Unlike Hancock's approach to quantifying performance against thermal stress under controlled conditions, they used field surveys to compare perceived comfort against self-assessed productivity, establishing a strong correlation between the two and a weak one between perceived and predicted comfort (PMV and Standard Effective Temperature). They noted that "perceived productivity fell slightly at temperatures above 25°C or below 21°C," a range in agreement with Schiller's observation that "office workers' sensitivity to changes in temperature was relatively flat, or at least broadly curved, over 3°C range near the optimum [of 22.5ºC]" (Schiller, 1990). Similar studies have not been performed in the tropics and one wonders if these productive temperature ranges are not equally applicable to hot-humid regions.

In knowledge-based economies like Singapore, the productivity of the workforce (their only resource) takes paramount importance. Singapore's founding Prime Minister, Lee Kuan Yew, named the air-conditioner as the most significant innovation of the millennium (Wall Street Journal, 1999):

> The humble air conditioner has changed the lives of people in the tropical regions. Before air-con, mental concentration and with it the quality of work deteriorated as the day got hotter and more humid. After lunch, business in many tropical countries stopped until the cooler hours of the late afternoon. Historically, advanced civilizations have flourished in the cooler climates. Now lifestyles have become comparable to those in temperate zones and civilization in the tropical zones need no longer lag behind.

Lee highlights the mental activity associated with comfort: with cooler conditions being conducive for work as contrasted to warmth for rest. Humphreys and Nicol also recognised the siesta routine as one adaptive response to heat (Michael A Humphreys & J Fergus Nicol, 1998). In the context of the productive working environment, an adaptive response that decreases productivity must be avoided, and hence it is imperative that thermal comfort for offices be defined with that understanding. Comfortable conditions for industries where workers are constantly physical activive, should be used with care when extended to the office context where drowsiness severely impacts productivity.

The effect of heat and drowsiness is familiar to most and validated by Mackie and O'Hanlon (Hancock, 1986) who found "that drivers exposed to hot environments exhibited decreased precision in steering control and an increased propensity toward error during the first 150 minutes of exposure, compared with performance when driving in thermally comfortable conditions." We well know that with long distance driving, the driver and passengers have different requirements for comfort by virtue of their differing mental activity, even if their environmental conditions, physical metabolism and clothing insulation are identical. Anecdotally, we also know that surgeons and nurses in the same operating theatre have different rates of perspiration, by virtue of different mental demands, not physical ones. Thermal comfort cannot be defined without the context of its associated mental activity.

This is an important contradiction with the observations of Humphreys & Nichol, who, in their field-studies in Pakistan, found that office workers in the tropics could tolerate much higher temperatures than stipulated in ASHRAE standards (M. A Humphreys, 1995). It would be of interest to compare this to workers who have experienced working in air-conditioned offices. This would help ascertain if performance had been diminished by heat adaptation. Since the brain accounts for such a significant concentration of heat, we postulate that part of the thermoregulatory response would be to reduce the firing rates of neurons to prevent overheating. If a similar experiment was conducted in Singapore, we can expect the results to be very different from Pakistan. A survey on the expectations for air-conditioning in young Singaporeans (Hitchings & Shu Jun Lee, 2008) found that:

> …The demand for air conditioning had largely reached the point where it was an expectation. In the public sphere, with regard to the office and the school, air conditioning was seen as essential not only for enhancing productivity but also as a courtesy towards employees and students who themselves worked hard to ensure the collective organizational success.

Prins, an anthropologist, in his polemic on air-conditioning (Prins, 1992) describes air-conditioning as “addictive”, “relentless” and “severe”. Whilst we may not use such emotive descriptors, there is a sense in which air-conditioning does alter one’s preferred temperature. A survey of literary works (Meyer, 2002) between British and Anglo-American writers found a change in preferred winter indoor temperatures from 14ºC during mid eighteenth century to 22-24ºC in the periods 1825-1840. These figures may need to be taken anecdotally (Meyer appears not to differentiate between radiant and air temperature), but we still agree with his thinking that energy efficient innovations coupled with affordable and abundant energy would cause climatic taste to be more exacting, as occupants become less tolerant to compromise, a phenomenon well expressed by Baker’s term “the irritable occupant” (Baker, 1996). The demand for cooling in the tropics parallels that for warmth in the cold, where increased affluence can drive optimum temperatures lower. This acclimatised addiction to air-conditioning parallels the effects of coffee: one does not realise the productivity boost until one has experienced it, after which there is no going back, and without which one gets highly irritable.

We have identified three conditions that have not been considered by either deterministic or adaptive comfort, and could possible explain the strong evidence supporting adaptive comfort with the contradictory strong demand for air-conditioning:

Mental metabolism
The considerable heat given off by our brains require more cooling there than for the rest of the body. Optimum temperature at an office will thus always be cooler than neutral.

Comfort as a function of mental activity
Conditions that are comfortable for a body to rest are not the same as that for the mind to work. A thermoregulatory response to heat acclimatisation is for mental activity to throttle down or, in a highly motivated individual, to perspire in the forehead.

Acclimatised addiction
A sense of comfort within a naturally ventilated space does not mean that workers are as productive as they could be in an air-conditioned space. With exposure to air-conditioning, workers develop a reliance on artificial cooling to maintain their heightened productivity.

4. COMFORT AND ENERGY

How then are we to resolve the need for comfort with energy constraints? If the deterministic model were correct, the primary focus would be on increasing plant efficiency and reducing building thermal load. In the adaptive model, considerable emphasis would be placed on education: to change the mindsets of governments, developers, building designers and building users that office workers can be comfortable without air-conditioning.

In the popular perception in Singapore, air-conditioning is here to stay. Increased affluence has turned a previous luxury to a present-day necessity. In many fast developing Asian cities, air-conditioning is even more imperative to cope with air pollution by providing a distinct micro-climate. Along these lines, we opine that air-conditioning cannot be denied to office workers, but instead of a single deterministic setting, a range should be provided that corresponds with the mental demands of each space: formal and personal areas being cooler to promote concentration, whereas informal, communal and creative spaces are allowed to approach warmer temperatures. Minimal ambient cooling should be provided in the general areas with extra cooling available on-demand, individually controlled and directed mostly to the head: a strategy akin to ambient and task lighting. These PEMs (Personal Environmental Modules) are connected from the central air-conditioning via the raised floor to each workstation, offering individual control over one’s personal space. A study done in San Francisco’s office buildings (Bauman, Baughman, Carter, & Arens , 1997) show marked increase in thermal satisfaction, with percent dissatisfied (those indicating they were very or moderately dissatisfied) falling from 11% (pre-PEM installation) to 0% (post-PEM installation).

Such a non-uniform environment builds on the delight of sensory fluctuations (Heschong, 1985), the satisfaction of a larger band with time variance (Baker, 1996) and the awareness of adaptive opportunity (Baker & Standeven, 1996). Ample adaptive opportunities should be provided for the worker to have flexible working environments as personal taste dictates: trips to the cybercafe with warmer conditions and a hot cappuccino, and back to a personal cool space for full-concentration on a specific task.

Air-conditioning efficiency need not lie solely in equipment improvements. The largest part on the chiller load is latent: to dehumidify external air. This load is decided by indoor air quality (IAQ) standards dictating relative humidity and air changes per hour. A notable innovation to cope with pollution has been adopted by the Paharpur Business Centre in New Delhi, India: all fresh air is collected at roof level, filtered, circulated through a rooftop greenhouse before entering the air-conditioning system and distributed to the 6-storey building. The plants reduce CO_2 concentration, enrich oxygen levels and remove volatile organic compounds. However the presence of plants further increase the latent load on the air-conditioning system through transpiration. This, and other dehumidification requirements, can be solved with sold adsorption desiccant systems. New generation zeolites which can be regenerated at 60-80ºC, temperatures achievable from flat-plate solar collectors (P. Mazzei, F. Minichiello, & D. Palma, 2002; Pietro Mazzei, Francesco Minichiello, & Daniele Palma, 2005), show great promise in tackling the latent load in a passive way. The option of removing moisture with heat (using desiccants) should be more actively adopted in the tropics where high insolation makes passive heating readily available, and the high enthalpy of air allows heat pumps to operate extremely efficiently (C.O.P. of 8-10).

Chilled beams should also play a larger role in tropical offices. Radiant cooling studies have demonstrated the efficacy of using chilled ceilings to achieve sensible cooling (Yellott, 1989). The asymmetric heat load of the body, with the head requiring the most cooling, means that the exposed head would benefit most from a chilled ceiling. To cope with the high dew-point of tropical air, chilled beams need to be adopted in conjunction with desiccant systems or conventional chillers that can pre-condition the air and maintain its humidity at a dewpoint under 13ºC. Well designed active chilled beams should have no condensation problems (Alexander & O'Rourke , 2008).

5. CONCLUSION

We have examined the divide between deterministic and adaptive theories and offered a few considerations to account for the gap: mental metabolism, and its associated comfort set-point, can explain the reliance office workers develop for air-conditioning through prolonged exposure. Whilst the financial price of providing cooling comfort remains inconsequential to employers, it is not without cost to a resource-constrained world. We have thus offered a few alternatives for future development in the hope that change can be brought by synthesising the two theories to achieve productive comfort in an adaptive interpretation of our desire for air-conditioning.

It must be added, that the resolution to comfort and productivity is not purely a technical one. Lee Eng Lock, an engineer known for notably improving building energy efficiency says (Berger, 1998):

> In engineering, you have to do things elegantly, which sometimes conflicts with doing it for the fees. In a fee, you are driven to jack up capital costs. If you make it elegant and cheap and better, you're working against your own financial interests

Lee's experience with increasing air-conditioning efficiency is not for the lack of technological advancements, but that "most of the problems in going to factor two or factor four reduction in energy are institutional barriers, consultants and architects and project managers and owner's rep[resentative]s stick to the tried and true (truly wasteful and inefficient) and resist any kind of change" (E. L. Lee, 2009). We have reverted to the very first principles of thermal comfort to establish our position in the scheme. We believe that addressing the mental metabolism of office workers is a crucial step to a meaningful change from the current state of air-conditioning.

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