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Dynamic Environment, Adaptive Comfort, and Cognitive Performance

Richard de Dear[1,*] and Fan Zhang[1,2]

[1]IEQ Laboratory, The University of Sydney, Sydney NSW 2006, Australia
[2]Griffith University, Southport QLD 4222, Australia

[*]*Corresponding email: Richard.Dedear@sydney.edu.au*

ABSTRACT
Since the invention of airconditioning over 100 years ago a central research challenge has been to define the indoor environmental temperatures best suited for occupants. The first scientific approach to this question was framed in terms of *optimising occupant thermal comfort*, commonly expressed as a U-function, symmetrical around a single optimum temperature for any given combination of the remaining comfort parameters (ISO, 2005). The inescapable conclusion drawn from such logic in the minds of risk-averse design engineers is that the only strategy able to reliably deliver occupant comfort is HVAC applied to sealed-façade architecture.

A rigorous scientific rebuttal of the "single temperature optimum" model of comfort came 30 years after PMV/PPD was first floated (e.g. de Dear and Brager, 1998; 2001). Known as the *adaptive comfort model*, a clear implication is that passive design solutions are capable of delivering comfortable internal environments across a broad swathe of climate zones, throughout most if not all of the year. But recently the "single temperature optimum" model has resurfaced, this time with its justification shifting away from the thermal comfort requirements of occupants towards their cognitive performance.

Beyond the building science domain, in disciplines such as psychology and ergonomics, the prevailing wisdom regarding temperature effects on cognitive performance is an *extended-U* rather than an inverted U function. The gist of the model is that cognitive performance is relatively stable throughout the moderate temperature range, but it rapidly deteriorates at the boundaries of thermal acceptability where stress drains the performers' attentional resources. The *extended-U* model has garnered broad acceptance across a range of disciplines with the notable exception of HVAC engineering and indoor air sciences. But the weight of research evidence tends to support the extended- rather than inverted-U model. In this paper the arguments regarding thermal effects on cognitive performance are critically evaluated.

KEYWORDS
Cognitive performance, arousal theory, temperature optimum, adaptive model.

INTRODUCTION
The effect of the thermal environment on performance and productivity has been a focus of interest among indoor environmental researchers for nearly a century, but most of that work has been conducted in relative isolation from the cognate disciplines of human performance evaluation. In his wide-ranging survey of the indoor environmental research domain Corsi (2015) observed that "… *indoor air scientists all too often work in narrow trenches, interacting primarily with those they have interacted with for years, content to dig more deeply into that of which they already have significant knowledge, and unaware of the*

connections that their work may have to those who dig in other trenches." This insularity is clearly evident in cognitive performance research theme.

The range of indoor temperatures deemed acceptable has a strong bearing on building energy requirements because it constrains the geographic scope as well as the seasonal duration when *passive* designs are able to achieve acceptable indoor environments. Secondly, the design temperature range indoors directly impacts energy required by active systems (HVAC) to achieve them. Up until about the end of the last century the range of indoor design temperatures was mostly couched in terms of thermal comfort. Simple comfort models suggested that a range of $\pm$1.5K around an invariant optimum temperature could ensure 90% occupant thermal acceptability (Fanger, 1970; ISO, 2005). However, more recent adaptive thermal comfort models have challenged these narrow temperature prescriptions with strong empirical evidence that indoor comfort temperatures are dependent on outdoor climatic conditions (e.g. de Dear and Brager, 1998, 2001). The adaptive comfort approach encourages warmer indoor temperatures in warmer climate zones and seasons, and *vice versa* in cooler climates and seasons. In response to this debunking of the comfort arguments HVAC peak bodies such as REHVA and ASHRAE have shifted their justifications for tight indoor temperature control away from occupant comfort towards occupant productivity (ASHRAE, 2013). Since these HVAC peak bodies exert a strong influence on air conditioning practices, HVAC-related energy and greenhouse gas emissions well beyond their European and North American jurisdictions, it behooves us to critically review the scientific evidence put forward in support of temperature effects on cognitive performance.

In this review we examine a broad collection of papers, all specifically examining the effects of thermal environment on cognitive performance, but from a variety of disciplinary perspectives *beyond* the indoor environmental sciences.

LITERATURE REVIEW

Moderate indoor thermal environments are far from hyper- and hypo-thermic scenarios because they pose no threat to health and safety. Nevertheless they are still capable of exerting adverse impacts on building occupants' cognitive performance, although the literature remains conflicted on the significance of these impacts. Two distinct theoretical perspectives have emerged. The first posits a dose-response relationship between the indoor thermal environment and cognitive performance, with *any* deviation from thermal optimum leading to a decrement in performance and productivity. The second position asserts that, depending on the thermal intensity of exposure, type of cognitive activity, and other attenuating factors, externally imposed cognitive demands can be absorbed by the buffering capacity or "cognitive reserve" of the subject, with little or no deleterious effect appearing until those adaptive resources are depleted.

The inverted-U model

Arousal theory (e.g. Duffy, 1962) has been ubiquitous in the stress literature. Alternatively known as the *Yerkes-Dodson law,* it postulates an *inverted-U relationship*. Performance of a particular task improves as arousal increases until reaching an optimal level for the task in question. Beyond this optimum, performance starts to decline when the arousal level continues to rise, and likewise with reductions below the optimal level of arousal. In regards to the effects of thermal environment on cognitive performance, the same inverted-U relationship has been assumed, substituting arousal level with the intensity of the environmental thermal load (e.g. Griffith and Boyce, 1971).

In the indoor environmental science domain, arousal theory and the associated inverted-U relationship, has held sway for several decades, judging by the number of citations it has received. Arithmetic relationships have been proposed by different researchers to quantify the performance decrement in percentage terms as room temperature (or thermal sensation) deviates from the single optimum. These functions have then been widely applied to cost-benefit analyses that trade off the costs of lost performance from the building's workforce against the costs of variations in building and building services design, retrofits, and operational facilities management practices. Seppänen and Fisk (2006) along with Seppänen et al. (2006) have emerged as the most influential studies in the indoor environmental science literature. Their meta-analysis collated 24 previously published studies, then fitted an inverted-U relationship to the summary data. The resulting model shows performance increasing as temperatures increased towards 21.6 °C, then decreasing in temperatures beyond 22 ºC. The same inverted-U relationship is mirrored in the *American Society of Heating, Refrigerating, and Air-Conditioning Engineers' Handbook of Fundamentals* (2013), but instead of room temperature, as in Seppänen et al. (2006), the *ASHRAE Handbook* shows the x-axis as room temperature relative to the optimal comfort temperature T_c for the group. Despite the large variance in data points in the meta-analysis, *ASHRAE's Handbook of Fundamentals* graph shows a smooth parabolic curve for performance, peaking at the optimum comfort temperature (corresponding to "*neutral*" thermal sensation), and then tapering off as soon as room temperature deviates from neutrality (Figure 1).

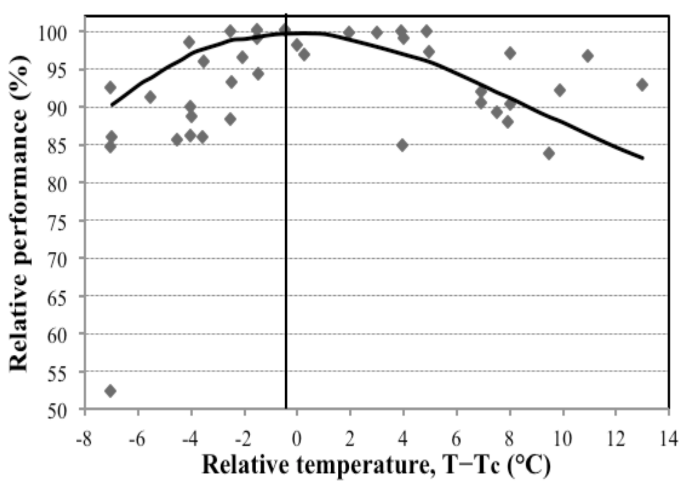

Figure 1 Relative performance of office work vs. deviation from optimal comfort temperature T_C (adapted from *ASHRAE Handbook of Fundamentals*, 2013).

The extended-U model

The extended-U model, initially proposed by Hancock and Warm (1989) and also known as the *Maximal Adaptability Model* contends that human performance remains relatively stable across a broad range, but rapidly deteriorates at the boundaries of thermal acceptability (Figure 2). Thermal stress exerts its adverse impacts on performance by consuming and ultimately depleting the performers' attentional resources (e.g. Kahneman, 1973). The normative zone falls in the middle of the continuum of input stress intensity, and it is here that zero compensatory effort is required of the participant in order for them to maintain optimal performance. The comfort zone encompasses broader conditions than the normative zone, but cognitive adjustments are easily accomplished within the comfort zone in order to maintain a near-optimum level of performance. However, when the environmental stress exceeds the comfort zone, attentional resources begin to be depleted. At first, equivalent or even improved performance can still be achieved by psychological adaptive behaviours such as attentional focus. Because of the central role played by psychological adaptability this region is referred to as the psychological zone of maximal adaptability in Figure 2. When the stress level continues to increase, human performance deteriorates as attentional resources begin to be depleted, indicated by the dashed line at the boundary of the psychological zone of maximal adaptability.

The extended-U model has garnered broad acceptance and currency across a range of disciplines with the notable exception of HVAC engineering and the cognate indoor environmental sciences. It has been confirmed by several authoritative literature reviews on this topic, none of which were published in the HVAC engineering and building science outlets. For example, Ramsey (1995) performed a meta-analysis on 160 individual performance studies and concluded that mental or simple tasks would most likely undergo negligible performance loss in hot environments, and may even be enhanced, at least for exposures under two hours. For perceptual motor tasks other than mental tasks, performance decrements were discernible only beyond 30°C WBGT (approximately 32°C air temperature at 50% RH).

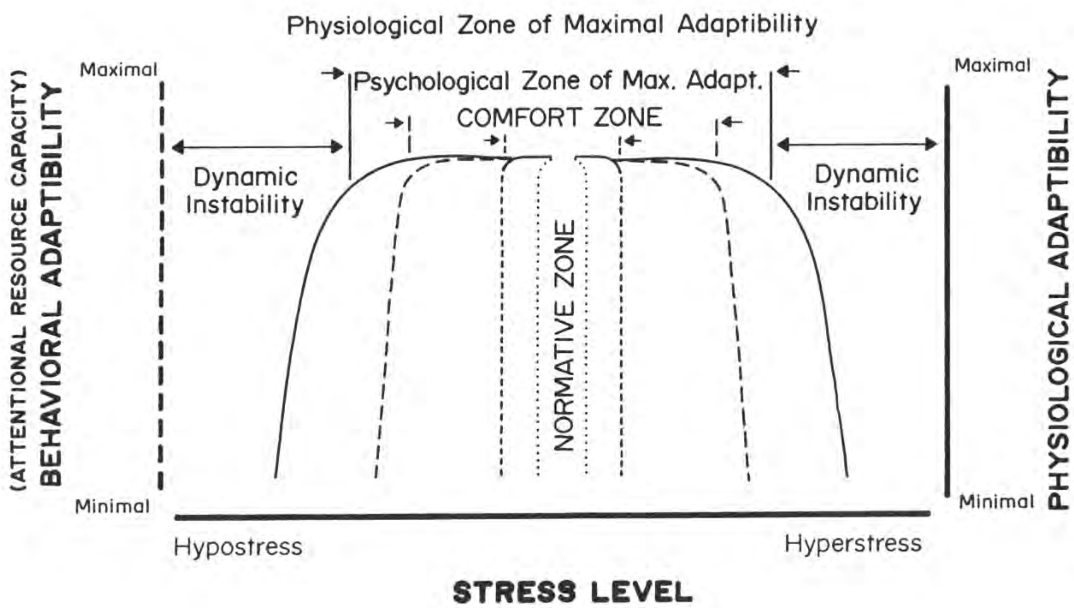

Figure 2 Extended-U model linking stress and performance (Hancock and Warm, 1989)

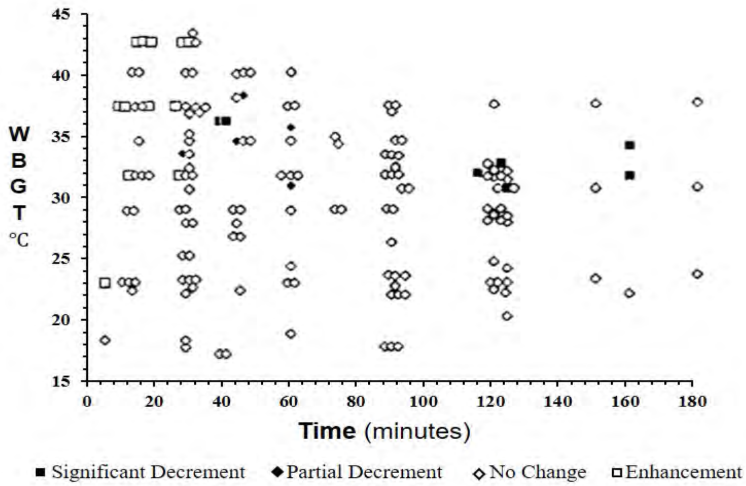

Figure 3 Mental or simple task performance under thermal stress (after Ramsay, 1995)

Another definitive meta-analysis by Pilcher et al. (2002) extracted 515 effects sizes from 22 original studies, and could find no effect of temperature on mental performance in the air temperatures ranging from 23-28.8ºC at 50% RH. This meta-analysis provides some of the strongest confirmation of the extended-U model. In Hancock et al.'s (2007) meta-analysis of 49 separate studies providing 528 effect sizes, the original studies were classified into four effective temperature ranges: below 25.7°C, 25.7°C–29.4°C, 29.4°C–35.2°C, and above 35.2°C. It was found that, "… *with the exception of the lowest temperature range, it is clear that the effect size variation sequentially increases across the three remaining categories. This gives rise to the proposition that performance is relatively stable over much of the temperature range but exhibits radical variation at the highest extreme* " (p.862) and this observation represents a core feature of the extended-U theory of stress and performance.

CONCLUSIONS

Notwithstanding its overly simplistic concept and methodological flaws throughout its empirical bases, the inverted-U relationship has held sway in the indoor environment research literature on thermal environmental influences on cognitive performance and productivity. Moreover, it has permeated engineering practice, as reflected in design guidelines and handbooks published by HVAC peak bodies. The dose-response inverted-U model has been uncritically implemented across broad swathes of the world's commercial building sector. Enhancements in HVAC equipment and control technology over recent decades have facilitated ever-tighter tolerances on indoor temperatures around a speciously defined performance optimum. Scientifically illiterate tenants and their facility managers have begun specifying overly stringent temperature clauses in their commercial office space lease agreements under the mistaken belief that they will maximise productivity from their human resources. However, this multidisciplinary review conducted in this paper finds the evidence for the single-temperature optimum dose-response relationship between indoor environment and occupant performance less compelling, which calls into question the crude cost/benefit of productivity decrements prevalent in the indoor environmental and HVAC engineering domains. Much stronger evidence in support of an extended-U relationship exists in literature published *outside* the usual for building science and indoor air fora.

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